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Pesticide lifecycle management in agriculture and public health: Where are the gaps?

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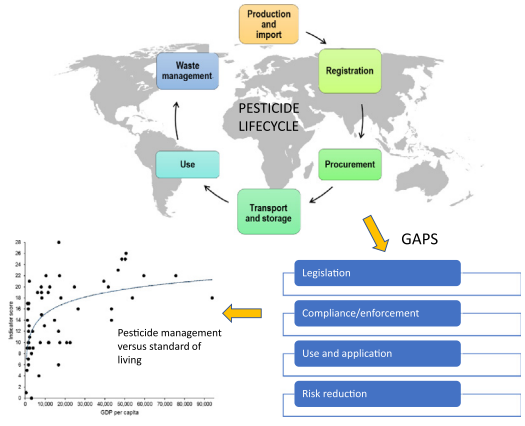
HIGHLIGHTS

- Gaps in lifecycle management of agriculture and public health pesticides were common.
- Low-income countries had most gaps, affecting pesticide efficacy and safety.
- Pesticide legislation and registration showed shortcomings in most countries.
- Inadequate measures against pesticide exposure and contamination were a concern.
- To reduce pesticide use, IPM and IVM should be prioritized in international policy.

GRAPHICAL ABSTRACT



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ABSTRACT

Pesticide lifecycle management encompasses a range of elements from legislation, regulation, manufacturing, application, risk reduction, monitoring, and enforcement to disposal of pesticide waste. A survey was conducted in 2017–2018 to describe the contemporary global status of pesticide lifecycle management, to identify where the gaps are found. A three-tiered questionnaire was distributed to government entities in 194 countries. The response rate was 29%, 27% and 48% to the first, second and third part of the questionnaire, respectively. The results showed gaps for most of the selected indicators of pesticide management, suggesting that pesticide efficacy and safety to human health and the environment are likely being compromised at various stages of the pesticide lifecycle, and at varying degrees across the globe. Low-income countries generally had the highest incidence of

Abbreviations: FAO, Food and Agriculture Organization of the United Nations; GDP, gross domestic product; HHP, highly hazardous pesticide; IPM, integrated pest management; IVM, integrated vector management; OECD, Organization for Economic Co-operation and Development; PPE, personal protective equipment; PPP, purchasing power parity; WHO, World Health Organization.

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Insecticide resistance
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Risk reduction
Vector control

gaps. Particular shortcomings were deficiencies in pesticide legislation, inadequate capacity for pesticide registration, protection against occupational exposure to pesticides, consumer protection against residues in food, and environmental protection against pesticide contamination. Policy support for, and implementation of, pesticide use-reduction strategies such as integrated pest management and integrated vector management has been inadequate across regions. Priority actions for structural improvement in pesticide lifecycle management are proposed, including pesticide use-reduction strategies, targeted interventions, and resource mobilization.

1. Introduction

Global pesticide use has steadily increased from an estimated 2.3 million tonnes of active ingredient in 1990 to 4.1 million tonnes in 2016 (FAO, 2020b). In addition, there has been a shift from use of insecticide products efficacious at relatively high dosages (organochlorines, organophosphates, carbamates) to highly potent products efficacious at low dosages of active ingredient (pyrethroids) but generally with lower mammalian toxicity (FAO, 2020b; van den Berg et al., 2012).

Pesticides are used for crop protection and pest and disease control. Inherent to the use of pesticides are the risks to the environment and human health. Therefore, there is a need to bring balance to their use in agriculture for the benefit of food supply and in public health for disease control. Recently, chemical pesticide use has been cited as one of the plausible causes for the drastically declining trends observed in insect biomass in protected areas (Hallmann et al., 2017). A new class of systemic insecticides, neonicotinoids, has also been found to adversely affect pollinators (Crall et al., 2018; Woodcock et al., 2017). In humans, acute occupational pesticide poisoning is a serious problem where farmer training programmes are inadequate, particularly in low- and middle-income countries (Jeyaratnam, 1990; Kishi, 2005), as is the problem of intentional self-poisoning with pesticides (Eddleston and Phillips, 2004; Gunnell et al., 2007). Also, pesticides that have been widely accepted and intensively used, such as the herbicide glyphosate, could have subtle and accumulative health effects in large human populations (Agostini et al., 2020).

There is broad international consensus about the need to implement strategies that reduce the reliance on chemical pesticides, notably by integrated pest management (IPM) in agriculture and integrated vector management (IVM) in public health (UNEP, 2010; WHO, 1997). However, where pesticides continue to be used in agriculture and public health, the adverse effects on human health and the environment should be minimized as much as possible. In this context, it is important to note that Sustainable Development Goal Target 12.4 is to achieve environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release into air, water and soil to minimize their adverse impacts on human health and the environment (UNSC, 2017).

The International Code of Conduct on Pesticide Management ('Code of Conduct') provides a voluntary framework for governments and other stakeholders to manage agricultural and public health pesticides throughout their lifecycle, including production, registration, import, transport, storage, application and waste management of pesticides and their containers (FAO/WHO, 2014). The Code of Conduct promotes best practices of pesticide use and pesticide use-reduction which ensure efficacy and reduce risks to human health and the environment. In addition, the Rotterdam Convention, Stockholm Convention and Basel Convention provide international legally binding instruments regarding aspects of pesticide management.

Previous surveys on aspects of implementation of the Code of Conduct revealed shortcomings at country level, with major contextual differences among countries with shortcomings in terms of legislation, regulation, quality control, safety and capacity (FAO, 1993; FAO, 1996; FAO, 2010; WHO, 2004b; WHO, 2011). The objective of this study was to identify main gaps in the contemporary global status on regulatory control and management of agricultural and public health pesticides, particularly in low- and medium-income countries, and to examine regional differences, as a basis for informing future strategies to optimize and prioritize global pesticide management practices. We hypothesized that the gaps were most pronounced in low-income countries.

2. Materials and methods

The survey questionnaire was prepared as part of a comprehensive assessment of the global situation of agricultural pesticides and public health pesticides (i.e. pesticides used to control disease vectors and pests of public health significance). The scope and content of the questionnaire were informed by the Code of Conduct (FAO/WHO, 2014) and a previous survey on public health pesticide management (WHO, 2011). The results of the comprehensive assessment have been reported in a different form in a separate document (WHO/FAO, 2019).

At country level, the topics of pesticide regulatory control, pesticide management in agriculture, and pesticide management for vector control in public health are commonly dealt with by separate government entities. Consequently, the questionnaire was developed in three parts, for distribution to the relevant authorities in the Member States of the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). The questionnaire was formally translated from English into French and Spanish and was sent as an editable text document.

Part I of the questionnaire covered pesticide regulatory control of both agricultural and public health pesticides, for completion by the national pesticide registration authority. Part II covered pesticide management in agriculture, for completion by the director of the agriculture department and/or the national coordinator for integrated pest management (IPM). Parts I and II were distributed by FAO via its regional offices and country offices to the national focal point in the Ministry of Agriculture in targeted countries. However, for some countries that did not have FAO country offices but that were member of the Organization for Economic Co-operation and Development (OECD), the questionnaire was sent through the national focal points for the OECD Working Group on Biocides. Details on responding countries are given in the comprehensive report (WHO/FAO, 2019).

Part III of the questionnaire covered public health pesticide application, with focus on vector-borne disease control, because of our interest in improving pesticide management within public health programmes. Insecticides directly applied on human skin (e.g., mosquito repellents, lice shampoos), household pest control products, and professional public health pest control products were not the focus and were only included where questions referred to public health pesticides in general. Part III was administered by WHO through its regional and country offices to the national focal point in the Ministry of Health in individual countries. The questionnaire was requested to be completed by the director of the main national vector-borne disease control programme (e.g. malaria, dengue), or (where applicable) by the national manager for vector control (i.e. person who has overall responsibility for entomological surveillance and vector control in the country). In cases were separate national programmes existed for different vector-borne diseases, the national malaria control programme manager or vector control manager was requested to coordinate completion of this part of the questionnaire.

In total, 194 countries were targeted for the survey in December 2017, which was comprised the Member Countries of FAO and the Member States of WHO. The allocation to regional groups differed from that used in the comprehensive report (WHO/FAO, 2019). FAO and WHO have different schemes for allocating countries to their regional groups. For the presentation of results in this paper, the United Nations Regional Groups of Member States was adopted (UN, 2020), which specifies the African, Asia-Pacific, Latin American & Caribbean, Eastern European, and Western European & Others Regional Groups of countries. The Western European & Others Group includes Australia, Canada, New Zealand and the United States of America.

By December 2018, responses to one or more parts of the questionnaire had been received from a total of 115 countries, with 56 responses to Part I, 52 responses to Part II and 94 responses to Part III (Table 1). This implies a response rate of 29%, 27% and 48% for Part I, Part II and Part III, respectively. All countries responding to Part II also responded to Part I; in addition, four countries responded to Part I but not to Part II. Some 35 countries responded to both Part I and Part III, and 31 countries completed all the three parts of the questionnaire.

The Western European & Others Group and the Eastern European Group had lowest response rates. Consequently, it was decided to pool the results of the 'Eastern European' and 'Western European & Others' Groups together into a 'European & Others Group'.

The results of the questionnaire included details that were beyond the objective of this paper, but which have been incorporated in a different form in a separate comprehensive report (WHO/FAO, 2019). A selection was made of those questions that were considered as indicators of pesticide regulatory control, pesticide management in agriculture, and pesticide management for vector control in public health. The indicators were selected to be elements without which the efficacy or safety of pesticides would be compromised, either directly or indirectly. Questions about context or details that were less critical for pesticide management were excluded, as were questions that appeared to be ambiguous in retrospect. Indicators of the same theme were grouped into 'categories' of pesticide management.

The selected indicators (see list with corresponding full questions in the Appendix) had binary responses, whereby a 'no' response signified a gap. The number of selected indicators was 28, 12 and 15, respectively, for Part I (pesticide regulatory control), Part II (pesticide management in agriculture) and Part III (pesticide management for vector control in public health), in accordance with the scope of each part.

For each indicator, gaps (as the number of 'no' responses) were examined per Regional Group using summary statistics. To examine the relationship between the status of pesticide management and the wealth per adult resident, we plotted the indicator scores for individual countries against the wealth per adult resident for that country, as measured by the gross domestic product (GDP) per capita, at purchasing power parity (PPP) (2017 international $) (World_Bank, 2019).

Table 1
Response to the questionnaire per Regional Group[a]. Indicated is the number of country responses (and percentage response rate; % RR) received to Part I (pesticide regulatory control), II (pesticide management in agriculture) and III (pesticide management for vector control in public health) of the questionnaire.

Regional groups[b]	Targeted countries	Responses to questionnaire					
		Part I		Part II		Part III	
		Countries	% RR	Countries	% RR	Countries	% RR
African	54	24	44	21	39	29	54
Asia-Pacific	55	14	25	13	24	30	55
Latin American & Caribbean	33	8	24	8	24	25	76
European & Others	52	10	19	10	19	10	19
Total	194	56	29	52	27	94	48

[a] Adapted from (WHO/FAO, 2019).
[b] Countries of the WHO Eastern Mediterranean Region were allocated to the African and Asia-Pacific Regional Groups.

3. Results

3.1. Pesticide regulatory control

Pesticide legislation was reportedly lacking in only 0–7% of the responding countries in the regions. However, public health pesticides and biological pesticides (or biopesticides; those derived from microorganisms or plants) were not covered by legislation in a substantial part (8–45%) of responding countries (Table 2). Legal provisions for re-registration, which allow for periodic re-evaluation of the need of pesticides, were lacking from a 7–25% minority of countries. Also, most countries lacked legal provisions on highly hazardous pesticides (HHPs), which are pesticides acknowledged to present particularly high levels of acute or chronic hazards to the environment or human health, especially when used on small farms with manual equipment (FAO/WHO, 2014). Policy to prevent and prohibit the production, sale, distribution or use of sub-standard or counterfeited pesticides was lacking from most countries in the African Group.

Pesticide registration is the formal process of data evaluation and approval of pesticide products for their sale, use and conditions of use. More than half of the responding countries reported missing published guidelines on the process and data requirements for registration covering all pesticides (Table 2). Major gaps in pesticide registration, indicated by low percentages, were apparent in the African and Latin American & Caribbean Groups, where most countries had only 10 or fewer persons working on pesticide registration.

Further gaps were reported in the legislation on manufacture and trade, including legislation on the authorization of facilities for pesticide manufacturing or formulation (with 12–48% of countries lacking this legislation) (Table 2). Particularly, legislation to control the retail, advertisement and on-line sales of pesticides was reported lacking from most countries, with 22–95% of countries across regions lacking specific legislation.

Legal provisions on safe storage, transport of pesticides, and proper disposal of pesticide waste and empty containers was a shortcoming in most countries outside of the European & Others Group (Table 2).

Regarding health risks, 87% of countries in the African Group reported lacking a central database on pesticide poisoning cases (e.g. at poison information centres) (Table 2). Guidelines and a training programme for teaching medical or public health staff how to treat pesticide poisoning cases were deficient in most countries across regions.

Regarding the monitoring and enforcement of pesticide legislation, major weaknesses were apparent in regions outside the European & Others Group; for example, routine monitoring and enforcement that detects problems at an early stage was reported from only 26–30% of African countries (Table 2). Some 21–75% of countries recounted shortcomings in the extent of monitoring and enforcement, and in the coordination between regulatory and enforcement agencies. Moreover, quality control of pesticides was hampered, particularly in the African Group, with countries lacking a national or regional laboratory for pesticide quality control and having inadequate laboratory capacity for analysing the active ingredient and physical-chemical properties (including relevant impurities) of samples of imported or locally available pesticides.

The status of pesticide regulatory control, as measured by the number of positive indicators in individual countries, showed a logarithmic relationship to the country-level GDP per capita ($r = 0.584$; 54 *df*; $P < 0.001$) (Fig. 1). Generally, the lowest-income countries had the poorest status of pesticide regulatory control, with implications for pesticide risks to human health and the environment, but the variation between countries in the number of positive indicators was large (Fig. 1). Encouraging examples of low-income countries were Burkina Faso,

Table 2
Situation on pesticide regulatory control. For each indicator is presented the percent of responding countries per Regional Group with a positive score (n indicates number of responding countries for each indicator).

Category		Indicator	Regional group							
			African		Asia-Pacific		Latin American & Caribbean		European & Others	
			%	(n)	%	(n)	%	(n)	%	(n)
General legal provisions	1	Pesticide legislation in place	92	(24)	93	(14)	100	(8)	100	(10)
	2	Public health pesticides covered by legislation	55	(22)	62	(13)	63	(8)	70	(10)
	3	Biopesticides covered by legislation in place	77	(22)	92	(12)	63	(8)	90	(10)
	4	Legal provisions for re-registration in place	75	(24)	93	(14)	88	(8)	90	(10)
	5	Legal provisions on highly hazardous pesticides (HHPs)	33	(24)	46	(13)	25	(8)	30	(10)
	6	Policy on sub-standard/counterfeited pesticides in place	25	(20)	85	(13)	100	(8)	100	(10)
Registration	7	Guideline on data requirements for pesticide registration	25	(24)	67	(15)	25	(8)	70	(10)
	8	Guideline on the process of pesticide registration	29	(24)	64	(14)	38	(8)	50	(10)
	9	More than 10 staff working on pesticide registration	25	(24)	57	(14)	13	(8)	90	(10)
	10	Identification of registered HHPs completed	58	(24)	75	(12)	75	(8)	50	(10)
Manufacture and trade	11	Legislation on manufacturing in place	52	(23)	86	(14)	88	(8)	67	(9)
	12	Legislation on pesticide labelling in place	83	(23)	93	(14)	100	(8)	90	(10)
	13	Legislation to control pesticide retail in place	43	(23)	31	(13)	38	(8)	78	(9)
	14	Legislation to control pesticide advertisement in place	39	(23)	38	(13)	13	(8)	67	(9)
	15	Legislation to control on-line pesticide sales in place	5	(21)	33	(12)	25	(8)	50	(10)
Storage, transport and waste management	16	Legislation on safe storage of pesticides in place	35	(23)	71	(14)	38	(8)	100	(10)
	17	Legislation on safe transport of pesticides in place	32	(22)	50	(12)	38	(8)	89	(9)
	18	Legislation on disposal of obsolete pesticides in place	36	(22)	54	(13)	29	(7)	100	(9)
	19	Legislation on empty containers in place	36	(22)	43	(14)	29	(7)	71	(7)
Health risks	20	Database on pesticide poisoning cases in place	13	(23)	58	(12)	71	(7)	75	(8)
	21	Guidelines for treatment of poisoning cases	32	(22)	67	(12)	14	(7)	63	(8)
	22	Training for treatment of poisoning cases	9	(22)	33	(12)	29	(7)	33	(9)
Monitoring and enforcement	23	Pesticide legislation to large extent monitored	26	(23)	64	(14)	25	(8)	90	(10)
	24	Pesticide legislation to a large extent enforced	30	(23)	57	(14)	38	(8)	80	(10)
	25	Adequate coordination between regulation and enforcement	58	(24)	79	(14)	75	(8)	100	(10)
	26	National laboratory for quality control in place	41	(22)	64	(14)	88	(8)	70	(10)
	27	Laboratory capacity to analyse active ingredients	38	(24)	86	(14)	88	(8)	90	(10)
	28	Laboratory capacity to analyse physical-chemical properties*	38	(24)	79	(14)	14	(7)	89	(9)

* Including relevant impurities.

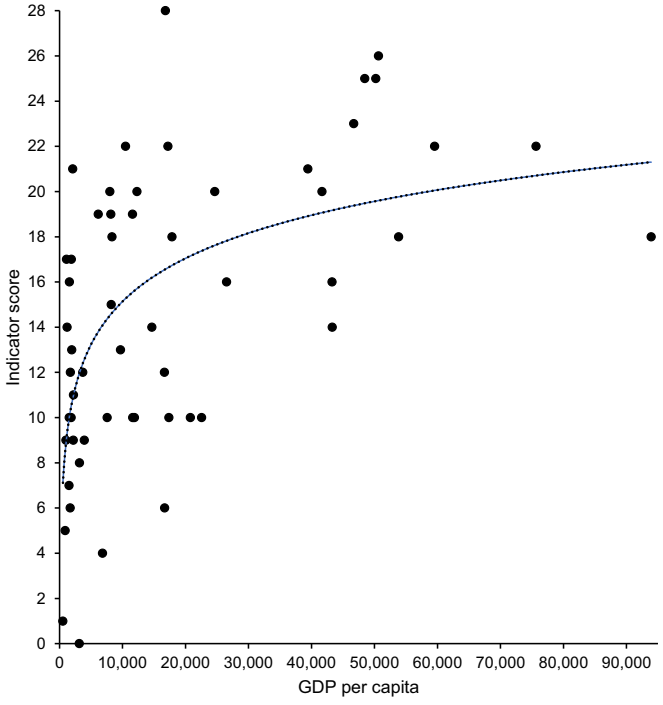

Fig. 1. Relationship between pesticide regulatory control and standard of living. The scatter plot shows the indicator score (i.e. number of positive among 28 indicators) versus GDP per capita, PPP (2017 international $) for individual countries ($n = 56$).

with 17; Zimbabwe, with 21; Myanmar, with 19; and El Salvador, with 20 positive indicators (out of 28).

3.2. Pesticide management in agriculture

National policy on IPM was lacking from 16 out of 51 responding countries, being least common in the African and Asia-Pacific Groups (Table 3). Most countries across regions, except the European & Others Region, reported they did not have a national programme to implement IPM throughout the country, and that inadequate lending or donor support was provided to IPM practices. Expertise and resources to manage insecticide resistance in agriculture were largely lacking by countries in the African and Latin American & Caribbean Groups.

Gaps in the category of pesticide application were apparent in all regions, except in the European & Others Group (Table 3). In about one third of the responding countries, agricultural spray workers who apply pesticides as a profession were not required to be licensed or certified, suggesting a lack of government control over the quality of spray application, and personal protective equipment (PPE) was reportedly unavailable, or available but not used, by spray workers, particularly among countries in the African Group. Most commonly mentioned reasons for not using PPE were non-affordability, discomfort and lack of awareness about health risks. A database to record the sale and use of agricultural pesticides, including data on import, export and manufacture, was lacking from roughly half of the countries, being least common in the African Group.

Further gaps were evident in the systems for monitoring pesticide residues in food or feed and pesticide contamination. A national system to monitor pesticide residues in food or feed items was missing from 15 out of 20 countries in the African Group (Table 3). A programme to collect data on pesticide contamination of the environment, and the

Table 3
Situation on pesticide management in agriculture. For each indicator is presented the percent of responding countries per Regional Group with a positive score (n indicates number of responding countries for each indicator).

Category		Indicator	Regional Group							
			African		Asia-Pacific		Latin American & Caribbean		European & Others	
			%	(n)	%	(n)	%	(n)	%	(n)
Integrated pest management (IPM)	1	National policy on IPM in place	57	(21)	69	(13)	86	(7)	80	(10)
	2	Programme on IPM implemented throughout the country	19	(21)	23	(13)	0	(7)	90	(10)
	3	Large degree of lending/donor support provided for IPM	24	(21)	30	(10)	14	(7)	25	(8)
	4	Expertise to manage insecticide resistance in agriculture	10	(21)	50	(12)	25	(8)	89	(9)
Pesticide application	5	Agricultural spray workers required to be licensed	67	(21)	46	(13)	75	(8)	100	(10)
	6	PPE available and used by spray workers	29	(21)	67	(12)	50	(8)	100	(10)
	7	Database in place on sale and use of agricultural pesticides	24	(21)	62	(13)	50	(8)	50	(10)
Residues and contamination	8	System in place to monitor pesticide residues in food/feed	25	(20)	67	(12)	89	(8)	90	(10)
	9	Programme in place to monitor environmental contamination	19	(21)	36	(11)	20	(5)	67	(9)
	10	Data on environmental contamination disseminated to public	16	(19)	33	(9)	40	(5)	67	(9)
Waste management	11	Guidance exists on sound disposal of pesticide waste	19	(21)	46	(11)	33	(6)	78	(9)
	12	System in place to collect empty containers from farmers	19	(21)	42	(12)	86	(7)	100	(10)

dissemination of data on environmental incidents or contamination to the public, were missing from two thirds of countries globally.

National guidance on the safe and environmentally sound disposal of agricultural pesticide waste, including guidance on a system to collect empty (used) pesticide containers from farmers were absent from 17 out of 21 countries in the African Group (Table 3).

The status of pesticide management in agriculture, as measured by the number of positive indicators in individual countries, showed a logarithmic relationship to the country-level GDP per capita ($r = 0.678$; 50 *df*; $P < 0.001$) (Fig. 2). The smallest number of positive indicators on pesticide management in agriculture was found among the lowest-income countries.

3.3. Pesticide management for vector control in public health

A national policy on integrated vector management (IVM) was reportedly lacking in approximately half of the responding countries in the African, Asia-Pacific and Latin America & Caribbean Groups, whilst in the European & Others Group only 20% of responding countries reported having an IVM policy (Table 4). A strategy for insecticide resistance management of disease vectors, and entomological expertise for monitoring of insecticide resistance, were least common in the European and Others Group and most common among countries in the African Group. It is imperative that all those responsible for decision-making and implementation of vector control programmes (e.g. programme managers) have been trained on pesticide management; however, this was the case in only 0–39% of countries across regions.

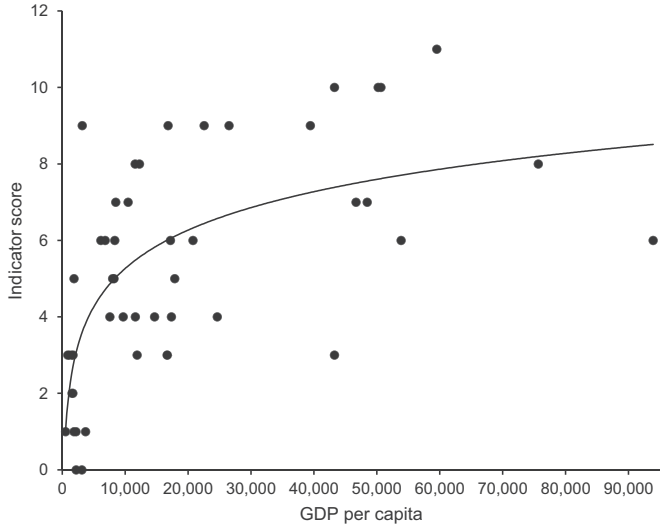

Fig. 2. Relationship between pesticide management in agriculture and standard of living. The scatter plot shows the indicator score (i.e. number of positive among 12 indicators) versus GDP per capita, PPP (2017 international $) for individual countries ($n = 52$).

In public health practice, vector control pesticides are procured by the diseases control programme according to the needs, and usually through public tenders. For procurement of vector control insecticides, a guidance document was lacking in 24–75% of countries. In 22–54% of countries, procurement was not carried out through public tenders, nor included after-sale stewardship commitments by the manufacturer or distributor (e.g. for labelling, training or monitoring) incorporated as a condition in procurement of vector control pesticide products (Table 4). Some 21–60% of countries across regions also lacked adequate, safe and secure facilities for storage of vector control pesticides at a central, government-controlled, level, particularly in the Latin America & Caribbean and the African Groups.

Regarding pesticide application, two thirds of countries across regions lacked a certification scheme for spray workers in vector-borne disease control programmes. In approximately three quarters of responding countries the use of appropriate personal protective equipment (PPE) for vector control operations by spray workers was mandatory (Table 4), however, actual use of PPE may be a challenge.

A programme to monitor the exposure of spray workers to pesticides used in vector control operations (e.g. through routine medical testing of staff) was largely deficient in responding countries across most regions (Table 4). Likewise, a scheme for quality control of spray equipment for vector control operations was largely absent but was more common among countries in the African Group. An information and awareness programme for the public, related to the use of public health pesticides, was lacking from half of the countries in the Asia-Pacific Group and from 61 to 88% of countries in other regions.

National guidance on the safe and environmentally sound disposal of pesticide waste from vector control was lacking from more than half of all responding countries, and a policy to prevent the accumulation of obsolete stocks of pesticides was lacking from two thirds of responding countries (Table 4).

The status of pesticide management for vector control in public health, as measured by the number of positive indicators in individual countries, showed no relation to the country-level GDP per capita ($r = -0.035$; 92 *df*; NS) (Fig. 3). The lower-income countries performed at least as well as did higher-income countries regarding pesticide

Table 4
Situation on pesticide management for vector control in public health. For each indicator is presented the percent of responding countries per Regional Group with a positive score (n indicates number of responding countries for each indicator).

Category		Indicator	Regional Group							
			African		Asia-Pacific		Latin American & Caribbean		European & Others	
			%	(n)	%	(n)	%	(n)	%	(n)
Integrated vector management (IVM)	1	National policy on IVM in place	46	(28)	63	(30)	56	(25)	20	(10)
	2	Strategy for insecticide resistance management in place	64	(28)	33	(30)	28	(25)	30	(10)
	3	Entomological expertise for resistance monitoring in place	86	(28)	67	(30)	64	(25)	30	(10)
	4	Vector control decision-makers trained on pesticide management	39	(28)	23	(30)	32	(25)	0	(8)
Procurement and storage	5	Guidance exists for procurement of vector control pesticides	57	(28)	76	(29)	58	(24)	25	(8)
	6	Procurement of vector control pesticides by public tenders	78	(27)	73	(30)	46	(24)	50	(6)
	7	Procurement includes after-sale stewardship commitment	46	(28)	67	(30)	60	(25)	56	(9)
	8	Safe facilities in place for storage of vector control pesticides	54	(28)	79	(29)	40	(25)	71	(7)
Pesticide application	9	Certification scheme exists for vector control spray workers	39	(28)	30	(30)	24	(25)	50	(8)
	10	Use of PPE mandatory for vector control operations	82	(28)	70	(30)	76	(25)	70	(10)
	11	Monitoring of pesticide exposure of spray workers in place	25	(28)	30	(30)	48	(25)	0	(9)
	12	Quality control of vector control spray equipment in place	57	(28)	33	(30)	28	(25)	30	(10)
	13	Public awareness programme on public health pesticide use	39	(28)	52	(29)	32	(25)	22	(9)
Waste management	14	Guidance exists on disposal of vector control pesticide waste	54	(28)	47	(30)	42	(24)	33	(9)
	15	Policy to prevent accumulation of obsolete pesticide stocks	39	(28)	37	(30)	20	(25)	22	(9)

management for vector control. For example, Sudan, Tanzania and Zambia all scored 13 positive indicators (out of 15).

An overall comparison of the positive indicator scores in Part I, II and III is presented in Fig. 4. The data show that the African Group scored lowest on pesticide regulatory control and pesticide management in agriculture, whilst the European & Others Group scored highest in these parts. The African Group scored highest on vector control in public health, where the European & Others Groups scored lowest. The Asia-Pacific and Latin American & Caribbean Groups had intermediate scores.

4. Discussion

Pesticide lifecycle management spans across legal issues, system issues (e.g. collaboration), and technical issues (e.g. insecticide resistance monitoring) – relying to an important extent on cross-sectoral linkages and coordination. Our study, in a nutshell, disclosed gaps for most of the indicators related to the pesticide life-cycle, from legislation, regulation, application, risk reduction, compliance enforcement and waste management. These gaps are similar to those in previous studies (FAO, 1993; FAO, 1996; FAO, 2010; WHO, 2004b; WHO, 2011), and suggest that pesticide management has been neglected within public sector and donor-funded programmes. The implication of these outcomes is that pesticide efficacy and safety to human health and the environment are likely being compromised at various stages of the pesticide lifecycle, and at varying degrees across the globe. The number and incidence of gaps is a matter of serious concern; however, the positive examples of low-income countries suggest that structural improvements are feasible.

Three shortcomings in the pesticide lifecycle are highlighted because of their prime importance for pesticide management and risk reduction: legislation, registration and worker protection. Pesticide legislation was generally present but was deficient in many countries. Where

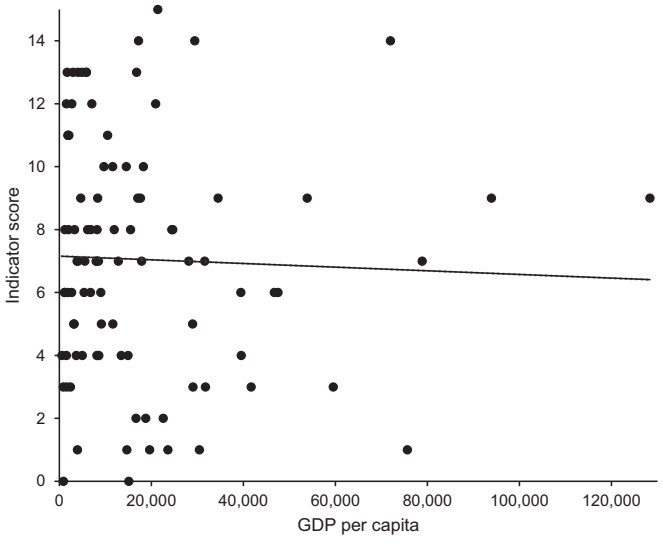

Fig. 3. Relationship between pesticide management for vector control in public health and standard of living. The scatter plot shows the indicator score (i.e. number of positive among 15 indicators) versus GDP per capita, PPP (2017 international $) for individual countries ($n = 94$).

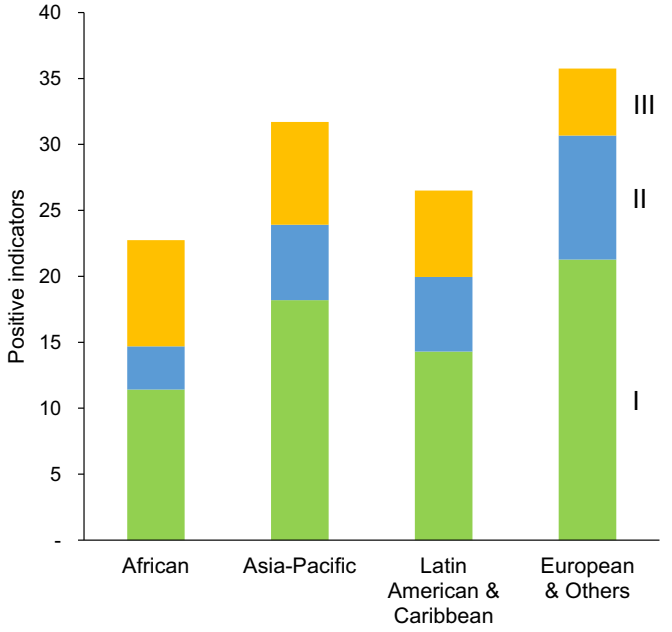

Fig. 4. Regional comparison between the average number of positive indicators in the three parts of the questionnaire. I, pesticide regulatory control; II, pesticide management in agriculture; III, pesticide management for vector control in public health.

legislation did not cover public health pesticides, the control of vector-borne diseases and pests of public health importance was likely affected, for example, through uncontrolled availability of substandard pesticide products. Where legislation did not cover biopesticides, these products may have been unavailable as safer alternatives to chemical pesticides. In addition, gaps in legal provisions for retail, advertising, online sales, storage and disposal of pesticide waste could undermine safety to human and animal health and the environment, for example by allowing availability for unacceptable purposes or allowing environmental pollution.

Pesticide registration is another area of concern. The formal process of data evaluation and approval of pesticide products is intensive and time consuming. Some high-income countries had hundreds of staff available to test, evaluate and monitor a multitude of pesticide products. However, many low-income countries and small-sized countries (e.g. small island developing states) lacked adequate capacity and national guidelines for the arduous task of pesticide registration; in fact, some countries had none or only one or two available staff. As a mitigating measure, countries in some regions (West Africa, Central Africa, Southern Africa, European Union, Andean countries) have established regional collaboration on pesticide registration to reduce workload, share available resources, and improve quality of the assessment. Also, FAO has recently developed a web-based toolkit to improve effectiveness, efficiency and safety of pesticide registration at country level, particularly in low- and middle-income countries (FAO, 2020a); the toolkit incorporates risk assessment data from countries of origin of pesticides. The lack of capacity extends to the compliance monitoring and enforcement of pesticide legislation and regulations, including pesticide quality control, and was particularly weak in the African and Latin American & Caribbean Groups of countries, possibly because enforcement has not been emphasized in priority setting and resource allocation.

Protection against occupational exposure to pesticides in agriculture and public health is a persisting weakness, particularly in tropical climates where use of personal protective equipment if available leads to discomfort (ILO, 2011), as is consumer protection against residues in food, and environmental protection against pesticide contamination. These shortcomings highlight the importance of pesticide use-reduction strategies. Poison information centres have an important function in advising pesticide registration authorities and informing and training of medical practitioners.

Integrated pest management (IPM) and integrated vector management (IVM) are general strategies of pesticide use-reduction in agriculture and public health, but support for policy and R&D and implementation of these strategies appears to be rather limited. The IPM concept was developed in agriculture more than half a century ago (Smith and van den Bosch, 1967; Stern et al., 1959), but implementation of IPM has been held back by scientific, political and business interests (Hokkanen, 2015; Parsa et al., 2014), whilst low-income countries lack adequate resources for research on IPM. The IVM concept in public health is more recent (WHO, 2004a; WHO, 2012), but has faced similar challenges with adoption (Alonso et al., 2017; Chanda et al., 2017). An immediate priority is that countries strengthen their capacity to manage insecticide resistance in agriculture and public health through rotational or mosaic application of insecticides with different modes of action and, eventually reducing reliance on chemical insecticides. Insecticide resistance is a special concern in contemporary malaria control efforts (Hemingway et al., 2016; Mnzava et al., 2015).

Low-income countries generally had the weakest systems of pesticide regulatory control and pesticide management in agriculture, with implications for protection of human health and the environment. For pesticide management in vector control, however, low-income countries were performing relatively well, as compared to higher income countries, which is probably attributable to recent large-scale investments in vector control by programmes for control and elimination of malaria, particularly in sub-Saharan Africa where malaria is the vector-borne disease with the highest burden (Korenromp et al., 2013; Warren et al., 2013). These investments have strengthened national capacities for insecticide resistance monitoring and quality assurance of pesticide application (Mnzava et al., 2015; WHO, 2018), but suggests that financing schemes that are less dependent on donor support need to be developed (KEMI, 2018). Conversely, countries in the European & Others Group, most of which have been relatively free from mosquito-borne diseases, scored lowest on several aspects of vector control, but recent threats of invasive mosquito vectors and re-emerging vector-borne diseases call for increased investment in vector control (Rezza, 2016; Schaffner et al., 2013; van den Berg et al., 2013).

A limitation of the study was that the focal points to which the questionnaires were addressed, and those who completed each part of the questionnaire, may not have had access to information regarding all questions. Another limitation was the low to moderate response rates of 29%, 27% and 48% for Part I, II and III of the questionnaires, respectively. There were no indications of a biased response (e.g. when countries with certain pesticide management characteristics are more likely to respond than others). Figs. 1-3 show that countries of all income classes were well represented in our sample. Consequently, the responses were considered to provide a reasonable to good sample representing the global situation. Nonetheless, if there was a bias, we expect that those with poorer pesticide management were less likely to respond – to hide shortcomings, in which case the actual situation on pesticide management could possibly be worse than we have captured in our survey. Russian-speaking countries and countries without offices of FAO and WHO were under-represented in the sample, thus contributing to the low response rate in the European & Others group.

What should be done to facilitate a structural improvement in pesticide lifecycle management at country, regional and global level? First, pesticide use-reduction strategies should be prioritized because these strategies address most of the concerns related to poor pesticide management (FAO/WHO, 2014). To advance the cause of IVM, WHO in 2017 launched the Global Vector Control Response 2017-2030, with a resolution adopted by the World Health Assembly (WHO, 2017). A similar strategic response would be needed in agriculture to revive IPM or equivalent strategies (e.g. agroecology), by prioritization on the international policy agenda.

Second, interventions need to be developed to strengthen the technical capacity, system support and legislative framework for pesticide lifecycle management at country level. An evaluation of intervention strategies concluded that support for regional policy development, thematic technical support across countries, and in-depth analysis and planning in selected countries had complementary effects (van den Berg et al., 2014). Further evaluation is needed in countries that previously conducted a situation analysis and action planning on pesticide management to study what worked and what did not work (WHO, 2013). Specific actions have been initiated by FAO in selected countries to re-evaluate national pesticide registries against the criteria for highly hazardous pesticides and to explore safer alternatives (FAO/WHO, 2016). Also, regional collaboration on pesticide registration and other categories of pesticide management has much prospect for low-income or small-sized countries, by conjoining their capabilities and resources and aligning their regulations and technical guidance. Evaluation of the accumulated experiences from several regional schemes and networks will be needed to identify lessons learned, which will assist international organizations in facilitating regional collaboration.

Third, a strategy for resource mobilization for pesticide lifecycle management needs to be developed. Funding streams within existing programmes should be catalysed. Specifically, programmes in agricultural and public health commonly prioritize targets of food production and disease control, but frequently this is done without tackling the risks caused by poorly regulated and improperly managed use of pesticides to achieve those targets. Donor or lending support for programmes in which pesticides are used should incorporate commensurate investment in strengthening the capacity and structures needed

for good practices of pesticide management. The example provided from malaria control and elimination programmes in sub-Saharan Africa has suggested that such investments can lead to a substantial improvement in critical elements of pesticide management. Financing schemes involving cost recovery fees, for example, to maintain registration, licencing and compliance monitoring, should be explored (KEMI, 2018). In addition, advocacy for increased domestic commitment of resources to pesticide lifecycle management will be crucial for a sustainable transition in countries towards strengthened pesticide regulatory systems.

5. Conclusions

The number and incidence of gaps in the critical elements of pesticide lifecycle management is a matter of concern across the globe, particularly in low- and middle-income countries. The implications of the gaps are that pesticide efficacy and safety to human health and the environment are likely being compromised at varying degrees across the globe. Pesticide legislation was generally present, but was deficient in many countries, and the capacity for pesticide registration was inadequate in most low-income countries. Protection against occupational exposure to pesticides, consumer protection against residues in food, and environmental protection against pesticide contamination are of concern in several geographic regions. Pesticide use-reduction strategies such as integrated pest management and integrated vector management have been given inadequate attention in policy support and implementation. Priority actions by national and international agencies, with targeted interventions and a strategy of resource mobilization, are urgently needed for structural improvement of pesticide lifecycle management.

CRediT authorship contribution statement

Henk van den Berg: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Validation. **Baogen Gu:** Methodology, Writing - review & editing, Validation. **Beatrice Grenier:** Methodology, Investigation, Writing - review & editing, Validation. **Eva Kohlschmid:** Methodology, Investigation, Writing - review & editing, Validation. **Samira Al-Eryani:** Investigation, Writing - review & editing, Validation. **Haroldo Sergio da Silva Bezerra:** Investigation, Writing - review & editing, Validation. **Bhupender N. Nagpal:** Investigation, Writing - review & editing, Validation. **Emmanuel Chanda:** Investigation, Writing - review & editing, Validation. **Elkhan Gasimov:** Investigation, Writing - review & editing, Validation. **Raman Velayudhan:** Conceptualization, Writing - review & editing, Validation. **Rajpal S. Yadav:** Conceptualization, Methodology, Writing - review & editing, Validation.

Declaration of competing interest

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

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Appendix A. Selected survey questions which were used as indicators

Part I: Pesticide regulatory control

	Indicator	Question
1	Pesticide legislation in place	Is there national or sub-national legislation (act/law/regulation) for registration and control of pesticides in your country?
2	Public health pesticides covered by legislation	Does the pesticide legislation (law/act/regulation) cover the registration and control of public health pesticides?
3	Biopesticides covered by legislation in place	Are biological pesticides, or biopesticides (which are: pesticides derived from natural materials, such as bacteria or plants), regulated under the same legislation chemical pesticides in your country?
4	Legal provisions for re-registration in place	Does your country have provisions in the legislation (act/law/regulation) for re-registration or periodic/regular review of the registered pesticide products?
5	Legal provisions on highly hazardous pesticides (HHPs)	Does your national legislation include special provisions on the registration, production, distribution or use of HHP?
6	Policy on sub-standard/counterfeited pesticides in place	Have policy or methods been established to prevent and prohibit the production, sale, distribution or use of sub-standard or counterfeited pesticides in your country?
7	Guideline on data requirements for pesticide registration	Are there any published national guidelines on data requirements for pesticide registration in your country?
8	Guideline on the process of pesticide registration	Are there any published national guidelines on the process of pesticide registration in your country?
9	More than 10 staff working on pesticide registration	How many persons work on pesticide registration in your country?
10	Identification of registered HHPs completed	Has your country identified HHPs registered or HHPs in use?
11	Legislation on manufacturing in place	Does your country have legislation (act/law/regulations) on the authorization or certification of pesticide manufacturing/formulator facilities?
12	Legislation on pesticide labelling in place	Does your country's pesticide legislation (act/law) include requirements for pesticide labelling?
13	Legislation to control pesticide retail in place	Does your country have legislation (act/law/regulations) to control retailers of all pesticides that are sold in retail (e.g. street shops)?
14	Legislation to control pesticide advertisement in place	Does your country have legislation (act/law/regulations) to control advertisement of all pesticides?
15	Legislation to control on-line pesticide sales in place	Does your country have legislation (act/law/regulations) regarding on-line sales of pesticides?
16	Legislation on safe storage of pesticides in place	Does your country's pesticide legislation (act/law/regulation) include provisions on the safe storage of all pesticides?
17	Legislation on safe transport of pesticides in place	Does your country's legislation (act/law/regulation) include provisions to ensure safe transport of all pesticides?
18	Legislation on disposal of obsolete pesticides in place	Does your country's legislation (act/law/regulation) include provisions to ensure proper disposal of obsolete pesticides?
19	Legislation on empty containers in place	Is there any legislation (act/law/regulations) to manage and prevent the re-use of empty pesticide containers?

(*continued*)

	Indicator	Question
Part I: Pesticide regulatory control		
20	Database on pesticide poisoning cases in place	Is a central database on pesticide poisoning cases or poisoning deaths maintained in your country?
21	Guidelines for treatment of poisoning cases	Are national guidelines available for treating pesticide poisoning cases?
22	Training for treatment of poisoning cases	Is a specific training programme in place to teach medical/public health staff how to treat pesticide poisoning cases?
23	Pesticide legislation to large extent monitored	To what extent is national pesticide legislation monitored in your country? Selected 'large extent' (routine monitoring detects problems at an early stage)
24	Pesticide legislation to a large extent enforced	To what extent is national pesticide legislation implemented and enforced in your country? Selected 'large extent' (routine monitoring detects problems at an early stage)
25	Adequate coordination between regulation and enforcement	Does adequate coordination exist between regulatory and enforcement agencies in relation to pesticide regulations?
26	National laboratory for quality control in place	Is there a national-level public pesticide quality control (testing) laboratory in your country?
27	Laboratory capacity to analyse active ingredients	Does adequate laboratory capacity (public/private) exist in your country to process and analyse the active ingredient of pesticide samples?
28	Laboratory capacity to analyse physical-chemical properties*	Does laboratory capacity (public/private) exist in your country to analyse physical-chemical properties including relevant impurities of samples of public health pesticides?
Part II: Pesticide management in agriculture		
1	National policy on IPM in place	Is there a national policy on integrated pest management (IPM) in your country?
2	Programme on IPM implemented throughout the country	Is there a national programme to promote IPM implemented throughout the country?
3	Large degree of lending/donor support provided for IPM	To what extent have lending institutions and donor agencies provided support to national IPM practices and improved IPM concepts and practices? Selected 'large degree'
4	Expertise to manage insecticide resistance in agriculture	Do you have sufficient resources and expertise to manage problems with pest resistance in the agricultural sector?
5	Agricultural spray workers required to be licensed	Does your country require agricultural pesticide applicators to be licensed or certified?
6	PPE available and used by spray workers	Is personal protective equipment (PPE) is available and used by pesticide applicators?
7	Database in place on sale and use of agricultural pesticides	Has a database been established to record data on import, export, sales, manufacture, and use of agricultural pesticides?
8	System in place to monitor pesticide residues in food/feed	Is a national system in place to monitor pesticide residues In food or feed items?
9	Programme in place to monitor environmental contamination	Has your country established programmes, or mechanism, to collect data on pesticide contamination of the environment (for example, to monitor pesticide residues in water bodies)?
10	Data on environmental contamination disseminated to public	Are data on environmental incidents or contamination disseminated to the general public?
11	Guidance exists on sound disposal of pesticide waste	Does a national guidance document exist on the safe and environmentally sound disposal of agricultural pesticide waste?
12	System in place to collect empty containers from farmers	Is there any system in place to safely collect pesticide empty containers from farmers / cooperatives in your country?
Part III: Pesticide management for vector control in public health		
1	National policy on IVM in place	Is there a national integrated vector management (IVM) policy for vector-borne disease control in your country?
2	Strategy for insecticide resistance management in place	Has a national strategy been developed for insecticide resistance management of vectors of human disease?
3	Entomological expertise for resistance monitoring in place	Does your country have entomological expertise for insecticide resistance monitoring of disease vectors at national level?
4	Vector control decision-makers trained on pesticide management	Have all those responsible for decision-making and implementation of vector control activities received training in sound management of public health pesticides?
5	Guidance exists for procurement of vector control pesticides	Is there a national guidance document(s), or informal guidelines, for procurement of vector control insecticides in your country?
6	Procurement of vector control pesticides by public tenders	Is procurement of vector control pesticide products by the Ministry of Health in your country carried out through public tenders?
7	Procurement includes after-sale stewardship commitment	Are after-sale stewardship commitments (e.g. labelling, training, monitoring), incorporated as a condition in procurement of vector control pesticide products in your country?
8	Safe facilities in place for storage of vector control pesticides	Are adequate, safe and secure facilities for storage of vector control pesticides available at central (government-controlled) level?
9	Certification scheme exists for vector control spray workers	Is there a certification scheme for pesticide applicators (spray workers) in vector-borne disease control programmes in your country?
10	Use of PPE mandatory for vector control operations	Is the use of appropriate personal protective equipment (PPE) for vector control operations (by spray workers, including from private sector operators) mandatory in your country?
11	Monitoring of pesticide exposure of spray workers in place	Is there a national programme to monitor the exposure of applicators (spray workers) to pesticides used in vector control operations in your country?
12	Quality control of vector control spray equipment in place	Is there a national scheme for quality control of application (spray) equipment for vector control operations (including space spray equipment) in your country?
13	Public awareness programme on public health pesticide use	Is there any national information and awareness programme, for the public, on use of public health pesticides in your country?
14	Guidance exists on disposal of vector control pesticide waste	Does a national guidance document exist on the safe and environmentally sound disposal of pesticide waste from vector control?
15	Policy to prevent accumulation of obsolete pesticide stocks	Does your country have a policy to prevent the accumulation of obsolete stocks of pesticides?

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