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Global status of DDT and its alternatives for use in vector control to prevent disease

Background document for the preparation of the business plan for a global partnership to develop alternatives to DDT

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Abstract

The global use of DDT for disease vector control is 4-5,000 tonnes of active ingredient per year. This substantial amount may increase as a number of countries are in the process of reintroducing DDT for malaria control. Both the costs and the effectiveness of DDT are dependent on local settings and merit careful consideration vis-à-vis alternative products or methods. Legislation and capacity to enforce regulations and good use and management practice for DDT is inadequate in many DDT-using countries. WHO recommends DDT only for indoor residual spraying, provided that several conditions are met. Concerns about the use of DDT are fuelled by recent reports of high levels of human exposure associated with indoor spraying amidst accumulating evidence on chronic health effects. There are signs that resistance in malaria vectors to the toxic action of DDT is spreading, though not (or not only) as a result of indoor spraying. The spectre of DDT illegally flowing into agricultural production systems raises broader environmental worries as well as a threat to international trade in export crops. Research on the fate of DDT applied in indoor residual spraying is still lacking. As immediate alternatives to DDT, effective chemical methods for vector control and transmission reduction are available. However, the arsenal of insecticides is limited and in certain areas the development of resistance is undermining the efficacy of insecticidal tools in malaria control while new insecticides are not expected in the short term. To be prepared for disease emergencies in the future, the continued effectiveness of insecticides needs to be safeguarded. A number of non-chemical methods have clearly contributed to successful malaria control, but more work is needed to study their effectiveness as main or supplementary intervention at programme level, tailored to local ecologies. In addition, a number of promising technologies are under development and need further investment. Important barriers and gaps in the development and implementation of DDT alternatives are discussed (some barriers also apply to use of DDT). A proposed solution is the support for long-term, integrated and multi-partner strategies of vector control. Integrated Vector Management, defined as a rational decision-making process for the optimal use of resources for vector control, provides a framework for developing and implementing effective technologies and strategies as sustainable alternatives to DDT.

The recommendations are:

i. External financial support for long-term, integrated and multi-partner strategies of malaria vector control is urgently needed;

ii. In the short term, immediate alternatives to DDT need to be accepted by donors and emphasized for implementation;

iii. Promising innovative technologies, particularly those that do not rely on chemical insecticides, need more emphasis in research and development;

iv. As the evidence base on some of the more serious and chronic health effects is mounting, the assessment of health risks of DDT needs to be re-visited and a system for monitoring exposure from IRS established;

v. Criteria for implementation of IVM need to be further developed and consolidated;

vi. A business plan for a global partnership to develop alternatives to DDT is needed.

Acronyms

DALY	Disability Adjusted Life Years
DDD	1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethane
DDE	1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethylene
DDT	1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane
FAO	Food and Agriculture Organization of the United Nations
LLIN	Long-Lasting Insecticidal Nets
IRS	Indoor Residual Spraying
ITN	Insecticide-Treated Nets
IVM	Integrated Vector Management
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WHO	World Health Organization

1. Introduction

The Stockholm Convention seeks the elimination of twelve chemicals or classes of chemicals, one of which is 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane, or DDT[1]. DDT is still used in indoor spraying primarily for control of vectors of malaria and visceral leishmaniasis. In negotiations that lead to the treaty, there has been concern that a sudden ban on DDT use could adversely affect the malaria burden. Thus, DDT was permitted to be produced and used for the purpose of controlling disease vectors in accordance with WHO recommendations and guidelines and when locally safe, effective, and affordable alternatives are not available.

Malaria is a complex parasitic disease mostly confined to tropical areas and transmitted by mosquitoes of the genus *Anopheles*. Each year, malaria causes several hundred million episodes of illness and approximately one million deaths[2]. Malaria-endemic countries are faced with a continuous and high cost of prevention and treatment of this disease. Vector control is crucial for the prevention of disease transmission which, if effective, reduces the infectious reservoir and the number of cases requiring treatment. Recent history suggests that insecticide resistance and drug resistance can contribute to a deterioration of the malaria situation[3]. Driving forces that exacerbate the malaria situation are *i.a.* poverty, civil unrest, deteriorating health infrastructures, as well as the continuous intensification of water resources development to meet the nutritional, fibre and energy needs of a growing world population[4]. The aggregate picture underlines the need for sustainable control efforts in view of future emergencies.

WHO has reaffirmed the importance of indoor residual spraying (IRS) as one of the primary interventions for reducing or interrupting malaria transmission in countries where this intervention is appropriate, including in situations of high malaria transmission[5]. WHO recommends DDT for use in indoor residual spraying only. DDT is still needed because there is no alternative of both equivalent efficacy and operational feasibility, especially for areas with perennial and long seasonal malaria transmission[6, 7]. “Countries can use DDT for as long as necessary, in the quantity needed, provided that the guidelines and recommendations of WHO and the Stockholm Convention are all met, and until locally appropriate and cost-effective alternatives are available for a sustainable transition from DDT”[6].

The Secretariat of the Stockholm Convention, the WHO and the United Nations Environment Programme (UNEP) Chemicals Division have in 2005 drafted a global strategic paper on the elimination of DDT, which remains to be completed. The Conference of Parties requested the Secretariat in 2007 to prepare, in collaboration with WHO, a business plan for promoting a global partnership on developing and deploying alternative products, methods and strategies to DDT for disease vector control. This partnership would establish a joint approach towards concomitantly reducing DDT use and the malaria burden, fostering collaboration, improving efficiency, and attracting financial support. The initiative is expected to assist in the implementation of future plans to build capacities, monitor and report on DDT use, stimulate development and deployment of alternatives and to eventually reduce and ultimately eliminate the use of DDT for disease vector control[8].

A provisional timeline for a three-phase plan for DDT elimination has been proposed by the Secretariat, on the assumption that the developed alternatives will be effective and will be acceptable to countries:

I. Preparation of a global business plan and partnership on developing alternatives to DDT and establishing the national capacities to deploy these alternatives (2007-2010)

II. Deployment of selected alternatives to DDT, resulting in a termination of DDT production (2009-2017)

III. Destruction of all remaining stocks and stockpiles of DDT by the year 2020.

In a brainstorming meeting with various key stakeholders held 11 October 2007 in Geneva, initial steps were outlined for the development of a global business plan for win-win strategies on malaria vector control that reduce the use of DDT. Steps included the preparation of a background document on the global status of DDT and its alternatives, the preparation of options for a global partnership, and meetings with broader representation from Parties and stakeholders to establish consensus on the preparation, content and implementation of a comprehensive business plan.

The objective of the present document is to provide a general background on the current status of DDT and its alternatives. The document covers various aspects of DDT, including production and use, legislation, cost-effectiveness, health effects, environmental effects, insecticide resistance, monitoring and evaluation. An outline is given on alternative chemical and non-chemical methods, and new developments. Cost effectiveness, current implementation, barriers and gaps of the alternatives are discussed. Possible solutions are presented. Information sources that were used in preparing the document are predominantly from scientific journals and published reports, supplemented where needed with unpublished reports and personal communications of the author with several stakeholders.

2. Status of DDT

2.1 Production, obsolete stock and use

2.1.1 Production

DDT is currently being produced in three countries, India, China and the Democratic People’s Republic of Korea (Table 1A). By far the largest amounts are produced in India, at one plant, for the purpose of disease vector control. In 2007, production in India was up 50% from the 2005 level. It is unclear whether this increase is in response to greater demand from Africa, because there is no information available on export. In China, the average annual production during the period 2000-04 was 4500 t of DDT, but 80-90% was used as intermediate in the production of Dicofol, an acaricide, and around 4% was used as additive in anti-fouling paints. The remainder, which was produced at a single plant, was meant for malaria control and was all exported. Recent information from DPR Korea indicates 160 t of DDT produced per year, mainly for use in agriculture (i.e. not acceptable under the Stockholm Convention) and a small portion for use in public health. The global production of DDT for vector control is estimated at 4550 t in 2003 and 4740 t in 2005. In 2007, production increased, with 6300 t produced in India alone. DDT is being formulated in Ethiopia and South Africa with ingredients imported from China. South Africa exports some of its formulated product to other countries in Africa.

Table 1. Annual global production and use of DDT (in 10^3 kg a.i.) in 2003, 2005 and 2007. "n.a." denotes data not available.

	Country	2003	2005	2007	Comment	Source[a]
A. Production of DDT for vector control						
1	China[b]	450	490	n.a.	for export	Pd
2	Korea DPR	n.a.	n.a.	5	plus 155 t for use in agriculture	UNITAR
3	India[c]	4100	4250	6344	for malaria and leishmaniasis	Pd, Ws, Dc
	Global production	4550	4740			
B. Use of DDT for vector control						
1	Cameroon	0	0	0	plan to pilot in 2009	WHO
2	China	0	0	n.a.	discontinued use in 2003	SC
3	Congo	0	0	0	plan for reintroduction	WHO
4	Korea, DPR	n.a.	n.a.	5	plus 155 t used in agriculture	UNITAR
5	Eritrea	13	15	15	epidemic prone areas	Qu, WHO
6	Ethiopia	272	398	371	epidemic prone areas	WHO, Ws
7	Gambia	0	0	0	use starting in 2008	WHO
8	India	4444	4253	3188	for malaria and leishmaniasis	WHO, Dc
9	Madagascar	45	0	0	plan to resume use in 2009	Qu
10	Malawi	0	0	0	plan to pilot in 2009	WHO
11	Mauritius	1	1	0	to prevent malaria introduction	Qu
12	Morocco	1	1	n.a.	for occasional outbreaks	Qu
13	Mozambique	0	308	n.a.	reintroduction in 2005	WHO
14	Myanmar	1	1	n.a.	phasing out	Ws
15	Namibia	40	40	40	long-term use	WHO
16	Papua New Guinea	n.a.	n.a.	n.a.	unknown amounts used	
17	South Africa	54	62	66	reintroduction in 2000	Qu, WHO
18	Sudan	75	n.a.	0	no recent use reported	Qu, WHO
19	Swaziland	n.a.	8	8	long-term use	WHO
20	Uganda	0	0	0	High Court prohibited use, 2008	SC, media
21	Zambia	7	26	22	reintroduction in 2000	Ws, Qu, WHO
22	Zimbabwe	0	108	12	reintroduction in 2004	WHO
	Global use	4953	5219	3725		

[a] Dc: Direct communication with national authorities; Pd: Project proposals submitted to the Global Environment Facility; Qu: Questionnaire on DDT by the Secretariat of the Stockholm Convention; SC: Documents published by the Secretariat; Ws: Workshop presentations in the context by country delegates of the Stockholm Convention

[b] The figure for 2005 was extrapolated from the total production. In addition to production for vector control, DDT is produced for Dicofol manufacture (approx. 3800 t p.a.) and for antifoulant paints (approx. 200 t p.a.).

[c] In addition, DDT is produced for Dicofol manufacture (approx. 280 t p.a.)

2.1.2 Use

It is estimated that 5000 t of DDT (in active ingredient; a.i.) were used for disease vector control in 2005 (Table 1B). Main use is for malaria control, but approximately 1000 t per year (20% of global consumption) is used for control of visceral leishmaniasis restricted to India. India is by far the largest consumer of DDT but, in 2007, use was one quarter down from the 2005-level. Mozambique, Zambia and Zimbabwe reported their recent re-introduction of DDT use. DDT use in Madagascar has declined with no use reported in 2005. Data on DDT use from some countries (Dominican Republic and Papua New Guinea) are not available or need verification. With the possible exception of the Dominican Republic, there is no reported use of DDT for disease vector control from the Americas. Use in Ecuador, Mexico and Venezuela was phased out in the year 2000. China has reported that no DDT has been used for disease vector control since 2003 and future use is reserved only for malaria outbreaks.

IRS programmes are expanding in Africa, the main driver being the US President's Malaria Initiative, and several countries are considering the introduction of IRS. Pilot programmes on IRS have started in Uganda and preparations for IRS are being made in Cameroon, Congo, the Gambia, Malawi and Nigeria. In some of these countries, a decision has not been made on whether to use DDT in their IRS programmes. Hence, the use of DDT may be increasing, especially in African countries, due to new countries initiating IRS programmes, including the use of DDT, and countries that are using DDT are expanding their IRS programs to stable transmission areas. This trend is probably as a consequence of the renewed WHO policy recommendations for malaria vector control. The current WHO policies on malaria control advocate the use of Insecticide Treated Nets (ITNs) and IRS in both stable and unstable transmission areas.

Workshops conducted by UNEP and WHO in the context of the Stockholm Convention have generated information which suggests that DDT is being traded on local markets for use in agriculture and termite control[9]. A framework or enforcement capacity of strict regulations is needed in many countries that use or plan to use DDT, to curb the problem of illegal trade and use of DDT.

Table 2. Available information on stock of DDT, most of which obsolete, per country (in t of product). Most data are preliminary and await thorough inventory; data from a large number of countries is missing. Data are from a variety of sources given in Table 1.

Country	Stock	Country	Stock	Country	Stock	Country	Stock
Algeria	189.0	Ecuador	1.6	Madagascar	0.0	South Africa	6.0
Angola	5.0	El Salvador	6.0	Mali	5.8	Sudan	234.0
Azerbaijan	5250.0	Eq. Guinea	0.0	Mauritius	116.0	Swaziland	0.0
Belize	13.0	Eritrea	46.7	Mexico	86.7	Sweden	0.0
Bhutan	0.0	Ethiopia	217.0	Mongolia	0.0	Switzerland	0.0
Bolivia	0.0	Finland	0.0	Morocco	37.0	Syrian AR	1575.0
Brazil	0.0	Guatemala	14.6	Myanmar	21.0	Thailand	0.2
Bulgaria	0.0	Guyana	150.0	New Zealand	11.6	Trinidad & T	24.0
Burundi	0.0	Honduras	0.0	Nicaragua	0.0	Uganda	0.0
Chile	0.4	Indonesia	0.0	Panama	5.0	UR Tanzania	170.6
China	11.0	Iran	30.0	PN Guinea	44.0	Uruguay	0.4
Costa Rica	8.5	Ireland	0.0	Poland	404.0	Vanuatu	0.0
Côte d'Ivoire	1125.0	Japan	943.8	Romania	6.6	Viet Nam	2.0
Denmark	0.0	Jordan	22.0	Senegal	0.3		
Djibouti	400	Lebanon	0.0	Solomon Is	0.8		
Dominican R	40.0	Macedonia	2.5	Somalia	0.0		

2.1.3 Stock and obsolete stock

There is a paucity of data on obsolete stock. The available information indicates large amounts of DDT are remaining in a number of countries; most of the stock is obsolete or of unknown quality (Table 2). Some countries (Angola, Botswana, Ecuador, the Philippines and Senegal) have reported keeping stocks in the event of malaria outbreaks, but such stocks could become obsolete or of poor quality if not used within the normal shelf-life of the chemical. Support for proper management of stocks should be incorporated in any donor-funded IRS programme which uses DDT. The transfer of DDT stocks between countries is not always documented nor reported and this poses a problem in tracking quantities of the chemical and to establish the quality of DDT being used[10]. A major effort is needed, e.g. through the Africa Stockpiles Programme, for the clean-up of obsolete stocks of DDT.

Conclusion: Global use of DDT is 4-5000 t per year, with India as the largest consumer. A number of countries are in the process of reintroducing DDT for malaria control.

2.2 Legislation and policies

Many countries that use DDT have inadequate legislation or lack capacity to implement or enforce regulations on pesticide management. Some countries lack any legislation in relation to DDT. Others have banned the importation and use of DDT in sectors other than public health, but lack legislation on the management of chemical pesticides including DDT. Some countries are planning to introduce new laws or amend laws in the context of their National Implementation Plans on Persistent Organic Pollutants. An additional problem which has been reported by several countries in Asia and Africa is the suspicion of illegal trafficking and use of DDT in sectors other than health, particularly in the agricultural and domestic environment[9]. Enforcement of pesticide regulation is often insufficient to avoid misuse or leakage outside the health sector, particularly in countries with long, porous borders. The transfer of DDT stocks between countries is not always documented nor reported and this poses a problem in tracking quantities of the chemical and to establish the quality of DDT being used.

The current WHO policies advocate the use of IRS as one of the three core interventions in management of malaria in both stable and unstable transmission areas. Twelve insecticides have been recommended for IRS by the WHO Pesticide Evaluation Scheme. The course of action promoted by WHO has been to retain DDT as part of the arsenal of insecticides available for IRS globally, in order to be able to manage insecticide resistance until suitable alternatives are available[6]. Nevertheless, DDT has not been subjected to the same requirements and risk assessment as the newer insecticides. The specifications and evaluations for DDT have not been updated since decades, while the other insecticides have to comply with contemporary, more stringent requirements.

The use of DDT in IRS is recommended only where the intervention is appropriate and effective in the local epidemiological situation. In this regard, the WHO has assisted countries to establish their capacity on the monitoring and management of insecticide resistance in malaria vectors. WHO, in collaboration with UNEP and the Food and Agriculture Organization (FAO) has been promoting the sound management of pesticides, and has developed guidelines for public health pesticide management[11].

The Global Strategic Framework for Integrated Vector Management (IVM) was developed under the auspices of the WHO to provide a policy framework for effective vector-borne disease control involving social mobilization, inter-sector collaboration and an integrated approach[12]. WHO is supporting the advancement of the IVM approach for vector-borne disease control[13].

Conclusion: Many countries that use DDT have inadequate legislation or lack capacity to implement regulations.

2.3 Cost and cost-effectiveness

One of the reasons the use of DDT for indoor residual spraying has been recommended by WHO is because of its cost-effectiveness[6]. Nevertheless, both the effectiveness and costs of DDT are dependent on local settings and merit careful consideration vis-à-vis alternative products or methods. A methodology for vector control managers to carry out economic evaluations of different vector control options has been available since 1993, but its use requires intensified promotion [14].

2.3.1 Effectiveness

DDT has been known as the only insecticide that can be used as single application in areas where transmission season is over 6 months, as supported by decades of programmatic experience. Nevertheless, published records describing the actual residual activity of DDT are rather few[15-18]. A standard duration of residual effectiveness for DDT (6 months or more) was set by a WHO Study Group[19] – data which have been much referred to[20]. However, considering the potential variability in residual action in the field (e.g. due to spray-able surface, climatic conditions), there is an urgent need for the strengthening of the contextual evidence base for the selection of an insecticide.

Other variables that determine the effectiveness of DDT (or any chemical, for that matter) are vector feeding and resting behaviour; repellent, irritant and toxic action; compliance level of residents to allow for spraying; the rate of re-plastering of inside walls; quality, coverage rate and timing of the intervention. DDT is only effective where vectors feed or rest primarily indoors. DDT is less suitable for spraying on painted or cement walls because it leaves stains on such surfaces. The malaria control programme in South Africa has thus adjusted its insecticide choice to the type of houses[21].

2.3.2 Cost

Direct costs of IRS are the procurement and transport of insecticide, training of staff, operations, awareness-raising of communities, safety measures, monitoring of efficacy and insecticide resistance, monitoring of adverse effects on health and the environment, storage and disposal. In a systematic analysis it was estimated that procurement of insecticides comprises 50-70% of total direct costs involved in IRS in low and medium income countries[22]. It is probable that insecticides are currently a smaller portion of IRS costs, but this needs to be substantiated.

In a comparison in 1990, the insecticide costs per house per six months of control were substantially lower for DDT than for other insecticides[23]. In a subsequent evaluation using 1995 prices, the cost of IRS was similar when using DDT, malathion, deltamethrin or lambda-cyhalothrin ($3.5-4.5 per house); this calculation was based on one spray for each insecticide[22]. An evaluation based on 1998 prices confirmed that the costs of DDT and alternative insecticides, pyrethroids in particular, have come closer due to an increase in the price of DDT relative to that of other insecticides[24]. In the latter study, insecticides were compared for their cost of providing six months of residual activity, allowing for local variability in prices and dosage of each chemical. The resulting cost range for DDT showed an overlap with that for some pyrethroids, but generally DDT was still the least expensive insecticide owing to its standard residual activity. This comparison will chance now that new formulations of pyrethroids with increased residual activity are available[25, 26], but further study is required.

Besides the direct costs of IRS, it is essential that the externalities or unintended costs of DDT (or alternative insecticides) to human health and the environment are included in the cost assessment. Also, use of DDT may have serious economic consequences for export of foodstuffs, as exemplified in the recent debate in Uganda[27] leading to a High Court decision in July 2008 to prohibit DDT use in that country. For pesticides in general, the external costs have rarely been addressed; the available studies have considered only the local or national-level costs, and were based on conservative estimates of acute poisoning and local environmental effects[28]. A comprehensive cost assessment of DDT versus its alternatives is urgently needed, which takes into account the potential costs of long-range atmospheric transport and long-term chronic health effects.

2.3.3 Cost-effectiveness

Studies on cost-effectiveness are scarce and have not incorporated the costs of externalities. The direct cost per disability-adjusted life year (DALY) that is averted by an intervention is a standard measure of health outcome which incorporates premature death and morbidity or disability. Results from an IRS programme using a conventional formulation of the pyrethroid lambda-cyhalothrin showed that the cost per DALY was $16-58[29]. To date, no comparative data have been published on cost-effectiveness in relation to DDT. Statements of high cost-effectiveness of DDT have been based on the positive experience from the malaria eradication era[30] supplemented with more recent results on reductions in malaria morbidity and incidence associated with the use of DDT[21, 31-34]. Operational issues of effective and sustainable IRS programmes remain a challenge for many countries[35], especially those with weak health systems, high transmission intensities or large target areas. Proposed and ongoing projects by the WHO, UNEP and UNDP are expected to establish a more solid evidence base for the effectiveness of DDT in relation to its alternatives[36]. The results will be crucial in future decision-making on vector management strategies for prevention of malaria. Unfortunately, the response of the Global Environment Facility, the interim financial mechanism of the Stockholm Convention, to support these initiatives as stipulated under the Convention has been slow.

Conclusion: IRS with DDT remains affordable and effective in many situations but, with regard to the direct costs, the relative advantage of DDT vis-à-vis alternative insecticides seems to be diminishing. The contextual evidence base on cost-effectiveness needs strengthening, and the external costs of DDT use vis-à-vis alternative insecticides require a careful assessment.

2.4 Health effects

The study on health effects of DDT is hampered by various methodological limitations. Studies have depended mostly on epidemiological data, often using case-control studies but lacking a solid counterfactual. A major hurdle has been to establish differences in the level and period of past exposure, a prerequisite for hypothesis testing. Cohort studies have the potential to provide stronger evidence of associations, but scientists have cautioned about interpreting the multiple outcomes of these studies for statistical reasons[37]. Experiments on animals allow for specific hypothesis testing under controlled conditions but are limited by their predictive power in humans.

2.4.1 Exposure levels

High levels of human exposure to DDT among those living in sprayed houses, most of who are living under conditions of poverty and often with high levels of immune impairment, have been found in recent studies in South Africa and Mexico[38-41], but contemporary data from India, the largest consumer of DDT, are lacking. The simultaneous presence of, and possible interaction between, DDT, DDE and pyrethroids in human tissue is another area of concern[42, 43]. Exposure of the foetus and young child occurs through the placenta and through lactation[43-45], and exposure of children and adults occurs through direct contact with DDT in the environment, indoor soil and household dust[46], and through the food chain. DDT accumulates in fatty tissue and is slowly released. Populations in adjacent regions and temperate regions may be indirectly affected by indoor spraying of DDT through long-range atmospheric transport. A monitoring system is needed for the assessment of trends in exposure to DDT[47], and allowing for the attribution of effects to IRS locally; in this regard, human milk is considered an important media to be monitored[48].

2.4.2 Evidence of disease outcomes

Several global assessments have been made on the evidence of health risks of DDT[49-52]. These assessments were conducted for specific purposes but not in relation to exposure through indoor residual spraying. Available studies have mostly focused on subjects in North America and Europe, who have generally been exposed to levels somewhat lower than those reported from areas with indoor residual spraying. Data on the health effects experienced by those living in sprayed homes are scarce[42]. As an indication, however, initial work suggests that non-occupational exposure through IRS is associated with impaired semen quality in men[40, 41].

Health effects of DDT and DDE most commonly suggested by studies in North America and Europe are: early pregnancy loss, preterm birth, decreased lactation, fertility loss, leukaemia, pancreatic cancer, neuro-developmental deficits, diabetes and breast cancer[37, 53-59]. In many cases the results have not been consistent between studies, but nevertheless these accumulating reports bear much concern particularly in relation to chronic effects. Breast cancer has been most rigorously studied and, even though the majority of results showed no causative association with DDT exposure[60], the latest evidence does indicate an increased risk in women who were exposed at a young age[61]. In addition, experimental studies on animals have demonstrated neurotoxic, carcinogenic, immunotoxic and reproductive effects attributable to DDT and DDE[49, 51, 62, 63].

The adverse health effects of DDT vis-à-vis the health gains in terms of malaria prevention require more attention. For example, a gain in infant survival resulting from malaria control could be (partly) offset by an increase in preterm birth and decreased lactation, both of which are high risk factors for infant mortality in developing countries. WHO is conducting a re-evaluation of health risks of DDT but progress has been slow. Alternatives to DDT should pose less risk to human health and the environment and be supported with monitoring data.

Conclusion: Indoor spraying with DDT is increasing the exposure intensity. DDT may still be needed for malaria control in the short term but, as the evidence base on some of the more serious and chronic disease outcomes is mounting, the adverse health effects of those at risk needs to be urgently revisited.

2.5 Environmental effects

As a persistent molecule, DDT has low to very low rates of metabolism and disposition, depending on ambient temperatures. In tropical environments with high temperatures and solar radiation, DDT is less persistent than in temperate environments. It is degraded slowly into its main metabolic products DDE and DDD, which have similar physico-chemical properties but differ in biological activity. DDT is emitted through volatilization and runoff. It is more volatile in warmer than in colder parts of the world which, through long-range atmospheric transport, results in a net deposition and thus gradual accumulation at high latitudes and altitudes[64]. Loss through runoff is low because DDT has a strong affinity for organic matter in soils and aquatic sediment, but is virtually insoluble in water. Half-lives of DDT have been reported in the range of 3-7 months in tropical soils[65, 66] and up to 15 years in temperate soils[1]. The half-life of each of its metabolic products is similar or longer. DDT readily binds with fatty tissue in any living organism and, due to its stability, bio-concentrates and bio-magnifies with increasing trophic level in food chains[67]. The half-life of DDT in humans is more than 4 years; the half-life for DDE is probably longer[42]. DDT is highly toxic to insects, shrimps and fish[68-70], and adversely affects the reproduction of wild birds through thinning of egg shells[71].

Most of the DDT and its metabolic products present in the global environment originate from its large-scale use in agriculture and domestic hygiene in the past. Current use under the Stockholm Convention is allowed only for indoor spraying for disease vector control. Thus, use is much smaller than in the past. Nevertheless, DDT that is sprayed indoors may end up in the environment, even if it is sprayed on walls according to best practice. Little attention has been paid to this issue. A simple modelling study predicted that 60-82% of DDT was physically removed from house walls within six months after spraying[72], but verification through empirical study is needed. Data from Brazil, India, Mexico and South Africa suggested that higher levels of DDT are found in water or soil samples in areas with DDT residual spraying than in areas without spraying[39, 73-76], but these results need further verification.

Conclusion: DDT used for indoor spraying could have adverse environmental effects, an aspect that requires close monitoring and investigation.

2.6 Vector resistance to DDT

2.6.1 History

As the number and size of programs which use DDT for indoor spraying is increasing, insecticide resistance is a matter of growing concern. Unless due attention is paid to the role of insecticide resistance in the breakdown of the malaria eradication campaign of the 1960s, resistance may once again undermine malaria control[77]. Since the introduction of DDT for mosquito control in 1946, DDT resistance at various levels has been reported from over 50 species of anopheline mosquitoes, including many vectors of malaria[78, 79]. In southern Greece, for example, a sharp increase in resistance in the main vector *Anopheles sacharovi* was observed in 1952, just 6 years after the onset of spraying in agriculture and vector control[80]. Subsequently, DDT resistance emerged in various anophelines, particularly in Central America, Southern Europe, the Middle East, and South and Southeast Asia[81]; nonetheless, malaria was successfully eliminated from many countries and was nearly eliminated from India and Sri Lanka[82]. In Africa, where the malaria eradication efforts were less intense, malaria vectors initially remained susceptible to DDT but, after it was first reported in Burkina Faso, Senegal and Togo[81, 83], DDT resistance developed fairly rapidly in that sub-region[84].

The use of DDT in agriculture in the past has been considered a major cause of DDT resistance in malaria vectors, as many vectors breed in agricultural environments[85, 86]. In 1963, Brown stated that “it is no mere coincidence that resistance of anophelines to either group of chlorinated hydrocarbon (i.e. DDT or dieldrin) is most serious in rice-growing and highly agricultural areas”[87]. At present, however, DDT resistance is thought to be triggered further by the use of synthetic pyrethroids in agriculture[88-90]. This is due to a mechanism of cross-resistance between pyrethroids and DDT, the so-called 'sodium channel' mutation affecting neuronal signal transmission, which is governed by the '*kdr*'-gene[91]. Vectors with the *kdr*-gene are resistant to both groups of insecticides. This has serious consequences for malaria vector control because pyrethroids and DDT are the two main groups of chemicals used. The *kdr*-gene is being recorded from an increasing number of countries thus, even in countries without a history of DDT use, resistance to DDT is emerging in populations of malaria vectors[92].

2.6.2 Current situation

Contemporary data from a range of sentinel sites in Africa indicate that the occurrence of resistance to DDT is widespread, especially in West and Central Africa[93, 94]. The major African vector *Anopheles gambiae s.s.* showed resistance to DDT in the majority of tests. Further, there is recent evidence of resistance in *An. gambiae s.l.* in Ethiopia[93, 95] – a country which for many years has been the largest DDT user on the continent. There are signs of DDT resistance in *Anopheles arabiensis* from Uganda, Cameroon, Sudan, Zimbabwe and South Africa[93, 96-100]. In Asia, the resistance problem is particularly widespread in India, the world's largest consumer of DDT. Multiple resistance to DDT and other insecticides in the major vector *Anopheles culicifacies* is known from many parts of the country[101-103] and has reportedly caused a major loss in effectiveness of the intervention[104]; nevertheless, the fate of vectors repelled by DDT also needs to be studied. Resistance has also been reported in *Anopheles sinensis* from China[105] and in *An. epiroticus* (formerly named *An. sundaicus*) from Vietnam[106]. Resistance and reduced susceptibility to DDT has been reported in several species of sandflies transmitting visceral leishmaniasis from India[107], though it is not clear how this affected programme performance.

2.6.3 Modes of action

Apart from its toxic action, DDT also has repellent and irritant properties[108]. Thus indoor spraying with DDT repels some of the mosquitoes from entering a house, and causes others to be irritated upon contact with the chemical and leave without biting and picking up a lethal dose of the toxicant[109]; those that come into contact with DDT are killed by the toxic action. The relative importance of these three modes of action in relation to malaria control is poorly understood. Standard testing of DDT resistance focuses on the toxic action[110], even though test methods are also available for the repellent and irritant action[111]. The dependence on one type of test has been questioned[112]. Repellent and irritant actions also need monitoring, even though their value has been controversial. On the one hand, an elevated repellent action was given as a reason behind the failure of DDT to interrupt malaria transmission in the period 1965-74, because less mosquitoes were killed[84]. On the other hand, there are reports of continued efficacy of DDT in malaria control despite resistance to the toxic action[112]. The repellent and irritant actions have the potential to reduce transmission of disease[92, 112] and in addition relieve the selective pressure for toxic resistance[81, 113]. Studies in the 1960s suggested that DDT resistant populations or strains of anophelines were less irritated by the chemical than non-resistant strains[81, 114]. Others reported an increase in repellent and irritant action, referred to as behaviouristic avoidance[115], but often it was not clear whether this effect was selected for by DDT spraying[116, 117]. Recent studies have indicated that the *kdr*-gene is associated with a reduced sensitivity to the repellent and irritant effects of pyrethroids in anophelines locally[118], but the effect in relation to DDT has not been studied.

2.6.4 Resistance management

An important lesson learnt from the experience with another vector-borne disease, oncocerciasis or river blindness, is that the development and spread of insecticide resistance is much slower when vector populations are under effective control [119], suggesting that integrated efforts to suppress malaria vector proliferation help prevent or delay the development of resistance. Effective monitoring and decision support systems can enable insecticide resistance to be detected at an early stage, which should lead to the implementation of changes in insecticide policy[21, 120]. However, the arsenal of unrelated insecticides remains limited[121, 122] which restrict the prospect for sustaining control. Even an intelligent insecticide resistance management strategy using rotations, mosaics or mixtures may not prevent resistance development[123-125].

Conclusion: Resistance to the toxic action of DDT appears to be spreading, but changes in the repellent and irritant action remains mostly unknown. Increased monitoring effort is needed.

2.7 Monitoring and evaluation

In the context of the Stockholm Convention, a process of reporting by each Party that uses and/or produces DDT is in place. A Register has been established for this purpose. By means of a questionnaire, Parties are asked to report every three years on their production, storage, use, conditions of use, regulations, control, resistance monitoring, safety, capacity, and alternatives in relation to DDT. However, the response rate has been poor. Parties that use DDT need trained personnel and a proper infrastructure to monitor the use, export and import of DDT. Donors and funding agencies aiding in the purchase of DDT should be obligated to provide adequate financial assistance to ensure that proper regulations are in place and should be required to provide a situation report to WHO or UNEP annually.

The DDT Expert Group meets every two years to report to the ensuing meeting of the Conference of Parties about the continued need for DDT. Hence, a major global assessment is made every 2nd and every 4th year, and a minor assessment, based on voluntary provision of information by Parties, every 6th year[7]. The WHO has been requested to assist in obtaining more in-depth information on certain aspects, through their direct engagement with the Parties concerned. Sentinel site systems are being established in the African Region to monitor resistance to DDT and other insecticides (see below). International vector resistance networks are absent in the other regions. Considering the potential hazards resulting from indoor residual spraying with DDT locally to human health and the environment, routine monitoring and special studies on health and environmental indicators are an essential component of any programme in which DDT is used, and need to be incorporated in project planning and cost-effectiveness evaluations (see section 2.3). Harmonization or standardization of methods and protocols tailored to the evaluation of indoor spraying is needed.

Conclusion: A reporting system on use of DDT is in place even though the response rate has been low. Donors aiding in the purchase of DDT should have accountability to report to WHO or UNEP. The monitoring of resistance and other side effects of insecticides needs strengthening.

3. Alternatives to DDT

A number of vector control methods are available as alternatives to DDT. Two of these, ITN and IRS (using alternative insecticides but also DDT), are being implemented on a large scale because of their proven impact on the malaria burden. Several other alternatives have been neglected in contemporary malaria control efforts, but have an important role to play. Table 3 summarizes 17 methods, which will be addressed in sequential order in the following sections.

Table 3. Alternative methods for malaria vector control, indicating the targeted vector stage, the potential risk, and required resources and delivery mechanisms.

Vector management method	Vector stage	Risk	Resources/delivery
Chemical methods			
1 Insecticide-treated bed nets	Adult	Resistance; toxicity	Free distribution; social marketing; commercial
2 Indoor residual spraying	Adult	Resistance; toxicity	Spray teams
3 Chemical larviciding	Larva	Resistance; effect on ecosystems	Spray teams
4 Repellents and attractants[a]	Adult	Toxicity	Local; commercial
5 Insecticide sponging of cattle[a]	Adult	Toxicity; resistance	n/a
Non-chemicals methods			
6 Source reduction	Larva	n/a	Local
7 Habitat manipulation	Larva	n/a	Local; agriculture sector
8 Irrigation management	Larva	n/a	Local; agriculture sector
9 Design of irrigation structures	Larva	n/a	Irrigation sector
10 House improvement	Adult	n/a	Local; development programs
11 Predation	Larva	n/a	Local; programs; agric. sector
12 Microbial larvicides	Larva	Resistance	Local; programs
13 Fungi[a]	Adult	n/a	n/a
14 Genetic methods[a]	Adult	To be studied	n/a
15 Botanicals	Larva/adult	Toxicity	Local
16 Polystyrene beads	Larva	n/a	n/a
17 Zooprophylaxis	Adult	n/a	n/a

[a] (partly) under development

3.1 Chemical methods

3.1.1 Alternative insecticides for indoor residual spraying

Spraying of residual insecticides to cover all sprayable surfaces inside dwellings is an efficacious method of malaria control. Compared to methods aimed at reducing vector population densities, its strength lies in its effect on shortening the life span of adult mosquitoes near their human targets, which has a critical impact on malaria transmission[17]. The bulk of evidence on the impact of IRS on transmission reduction is from observational data obtained during the malaria eradication era and additional small-scale trials in the 1950s and 1960s[84, 126]. In northern Nigeria in the 1970s, IRS also substantially reduced malaria transmission[127], though not as much as in western Kenya in the same period[127, 128]. The difference was attributed to the greater indoor resting habit of the local vector in Kenya. Recently, the impact of IRS has been confirmed by unpublished country reports and by several studies, for example, from the carefully controlled spray operations combined with chemotherapy in focal areas of South Africa and Mozambique[21] and from village-level trials in Pakistan[129]. However, there is little information on effectiveness and operational feasibility of IRS in other endemic countries in Africa, some of which have recently reintroduced IRS or are planning to do so.

Twelve insecticides belonging to four chemical classes are recommended for IRS in vector control of malaria and leishmaniasis[130], which collectively address only three different modes of toxic action[121]. Pyrethroids appear to be the most cost-effective alternatives to DDT in malaria control[24]. However, resistance to pyrethroids is already widespread, and the occurrence of cross-resistance between DDT and pyrethroids severely limits the choice of insecticides. South Africa was forced to reintroduce DDT after failure of pyrethroids, due to one of the locally extinct vectors returning and having acquired pyrethroid resistance (not *kdr*-type) elsewhere[131, 132]. Sandfly vectors of leishmaniasis remain susceptible to non-DDT insecticides in India.

There are two new developments with regard to IRS. First, some existing insecticides not currently available for public health purposes showed potential for use in IRS in areas with pyrethroid resistance[133, 134]. Second, new formulations of existing pyrethroid and non-pyrethroid insecticides with prolonged residual activity are being developed as alternatives to DDT[135]. Two of these, slow-release capsule and granule formulations of pyrethroids (lambdacyhalothrin-CS and deltamethrin-WG) are already available on the market; other products are expected in the coming years. In the selection of alternatives to DDT, a comparative assessment of health and environmental risks is required.

3.1.2 Insecticide-treated bed nets

The main current alternative to IRS is the use of insecticide-treated bed nets (ITN)[136]. The insecticide enhances the protective effect for the person under the net, but also has a beneficial effect on the community at large[137-139]. ITNs have been convincingly shown to cause substantial reductions in all-cause child mortality both, under experimental[140] and operational conditions[141-143]. It is effective in highly endemic settings by reducing the risk of severe disease, particularly in infants and young children before they have acquired a certain level of natural immunity[144]. ITN may also be effective against leishmaniasis, depending on the biting behaviour of the local vector[107, 145]. Two categories of ITNs are available: conventionally treated nets and long-lasting insecticidal nets (LLIN). The former needs regular retreatment – a follow-up action which has proven difficult to achieve at field level. The latter is a relatively new technology which retains the efficacy for at least three years, thus removing the need for retreatment[146-148]. Pyrethroids are the only chemical group recommended for use in ITNs[149, 150]. WHO currently recommends the purchase of LLIN[151], but scaling-up of LLIN to meet the demand is a challenge[152]. Disposal of LLIN is a potential problem.

There are several new developments on ITN. Research has been initiated on the use of non-pyrethroid insecticides for treatment of bed nets to cope with the problem of resistance. Carbamates and organophosphates were found to be efficacious but lack repellent and irritant properties necessary to protect people sleeping under damaged nets[153]. In an area of pyrethroid resistance, high effectiveness was found in field trials using nets treated with carbosulfan as a model for non-pyrethroid insecticides and ‘two-in-one-nets’ with both carbosulfan and a pyrethroid, but safety issues are a major concern[154]. An experiment with mosquito netting treated with a microcapsule formulation of DEET showed repellent, irritant and toxic activity for a period of at least six months under laboratory conditions[155]. Finally, at least one new insecticide for ITN is being developed, with novel chemistry utilizing an existing insecticide backbone[135]. It is critical that this unique product, once entering the market, be reserved solely for public health purposes, thus reducing the risk of insecticide resistance in the future. New ITN products are not expected to come to market in the short term. Human risk assessment following WHO methodology is an essential component of these developments.

3.1.3 Larviciding

The use of chemical insecticides as larvicides to control mosquito breeding in aquatic habitats such as the edges of swamps and lakes, pools, and riversides can in certain settings play an important role in malaria control. Larviciding was the main intervention responsible for eradication of introduced *Anopheles gambiae s.l.* populations from North-eastern Brazil in the 1930s and in the Nile Valley of Egypt in the 1940s[156, 157], though larviciding is not necessarily a recommended option for control in situations where this species breeds in numerous types and sizes of water bodies. WHO recommends four organophosphate insecticides for larviciding[158], but their broad-spectrum effect of these chemicals when applied to aquatic ecosystems are a concern. Larviciding and other larval control methods are promising supplementary interventions to IRS and ITN where they are applicable and feasible, particularly in urban settings. Used engine oil has been used in small confined pools used to suffocate mosquito larvae but, in warm climates, the oil layer can evaporate within days. Insect growth regulators are specific hormone analogues which have shown to reduce vector populations and malaria incidence when applied to an irrigation system[159] or to an area where breeding was confined to gem pits and stream bed pools[160]. These results indicate that insect growth regulators can be a cost-effective tool for malaria control when breeding sites are known. Generally, larviciding for malaria vector control is effective where (and when) breeding sites are easily accessible and manageable.

3.1.4 Repellents and attractants

Chemical repellents could have a useful supplementary role to ITN[161]. Repellents are available for application to the skin or clothes or as repellent soaps, or as low-cost vaporizers. Some novel compounds have shown to be promising candidates for mosquito repellents[162]. Moreover, innovative work is in progress on the biochemical mechanisms underlying host finding and feeding through identification of the key components of human odour that are responsible for differences in attractiveness to malaria vectors. Potential applications are novel mosquito attractants and repellents for use in trapping and personal protection[163, 164].

3.1.5 Insecticide sponging of cattle

In Pakistan, where primary vectors prefer to feed on domestic animals, it was demonstrated that livestock treatment with deltamethrin reduced the vector populations and lowered malaria incidence. Efficacy was similar to that of indoor spraying but the cost was 80% less, indicating that insecticide sponging of livestock is a promising method in certain settings, though probably not in Africa[165].

Conclusion: Effective chemical methods of vector control and personal protection are available for malaria control but the arsenal of unrelated insecticides is limited. Effects of alternatives on human health and the environment need to be assessed. Scaling-up of effective interventions to a level so as to have impact on transmission intensity and disease burden is a challenge.

3.2 Non-chemical methods

Environmental management for vector control is the collective term for manipulating or modifying environmental factors or their interaction with humans to reduce vector breeding and to reduce contact of vectors with humans[166]. Prior to the advent of synthetic insecticides, the control of malaria vectors depended primarily on environmental management, aimed to suppress mosquito breeding in areas of economic importance. A meta-analysis of studies mostly from that period showed that environmental management substantially reduced malaria risk[167]. A distinction is commonly made between environmental manipulation and modification, to denote temporary changes and long-term transformation of vector habitat, respectively. Specific non-chemical methods are briefly discussed below.

3.2.1 Source reduction

Source reduction is the elimination of vector breeding habitat through drainage, land levelling, filling, or covering, to prevent egg deposition and control larval development. Human-made breeding habitats are generally the easiest targets, particularly in urban settings. Unless vector breeding is concentrated in a few spots, the participation of local communities in source reduction is crucial[168-171].

3.2.2 Manipulation of natural habitat

Habitat manipulation involves the management of water bodies or impounded water to prevent vector breeding. Depending on the habitat preference of local vectors, measures include clearance of aquatic vegetation, provided sunny or shaded conditions, flushing of streams or canals through the sudden release of impounded water upstream, or straightening of river banks[172-174].

3.2.3 Irrigation management

Irrigated agriculture and its canal structure provides ample breeding habitat for a number of major malaria vectors. Mosquito breeding is potentially controlled through a combination of land levelling, bunding and intermittent irrigation. This has proven successful in rice-growing regions in different parts of the world[175, 176]. An added benefit is that the rice crop generally performs better under intermittent irrigation than under continuous flooding[177].

3.2.4 Design of irrigation structures

New irrigation systems or dams cause drastic changes in human settlement patterns, human circulation and in the presence of standing and flowing water. The cumulative impact of many small dams can be equally or more important than that of one mega-dam, as was shown in Ethiopia[178]. Planning to avoid health risks is essential at the design stage of irrigation systems and dams[179], and involves health impact assessment and the formulation of a public health management plan.

3.2.5 House improvement

House improvement can contribute significantly to malaria transmission control. Plastering of walls and ceiling fills the crevices that serve as refuge for adult mosquitoes. A study in Sri Lanka showed that the risk of malaria was 2.5 times higher in poorly constructed houses than in houses of good construction[180]. Moreover, screening of houses or sleeping quarters to keep mosquitoes out at night is a protective option for houses with solid walls[181].

3.2.6 Predation

Mosquito larvae are easy prey for aquatic predators, because of their poor abilities to fend off enemies or to escape. Thus natural enemy complexes are effectively controlling mosquito breeding in most natural habitats – a fact that is often taken for granted. In general, predators are less common and predation less prevalent in human-made or temporary habitats than it is in large, permanent habitats[182-184]. Predation can be enhanced through the conservation of existing predator complexes or through introduction of agents from outside. Broad-spectrum insecticides applied are commonly used to protect irrigated rice but have proved to be mostly unnecessary for production purposes of rice[185]. Thus, most arthropod predators are killed and recover only slowly, which can result in a resurgence of mosquitoes and related Diptera as demonstrated in Kenya and Indonesia[183, 186]. Larvivorous fish have frequently been reared and released for controlling vector breeding in small water tanks and wells, but successes have generally been limited to more or less permanent water bodies[172, 187]. Programmes where larvivorous fish was integrated with other malaria control methods have reported major reductions in malaria incidence[188-190], but the relative contribution of fish remains to be investigated.

3.2.7 Microbial larvicides

Two species of bacteria, *Bacillus thuringiensis israelensis* and *B. sphaericus*, produce toxins that are used in formulations as microbial larvicides. The toxins lack the adverse side effects of synthetic chemicals because they are specific to mosquitoes, instable, and have a lower risk of resistance development[191]. Recent field trials and pilot projects have shown good potential of both bacteria to manage mosquito breeding and to reduce biting rates[192-196]. In addition to the work on conventional microbial strains, recombinant bacteria are being developed with more than 10 times higher toxicity, but this technology has not yet been tested in the field[197].

3.2.8 Fungi

Insect pathogenic fungi have only partly been explored for their potential in vector control. A selected fungus has shown promising results for controlling adult *Anopheles* mosquitoes [198]. When applied to surfaces inside houses where female mosquitoes rest after blood meals, the fungus infects and kills the insects upon contact without being ingested. Studies have predicted that malaria transmission could be substantially reduced by this method[199, 200], but several issues related to residual activity, resistance development and effects on non-target organisms remain to be addressed[201]. Other biological control agents are specialist parasitic nematodes attacking the larval stages of mosquitoes. Field trials have shown potential to reduce anopheline larval densities[202].

3.2.9 Genetic methods

Two genetic approaches to controlling malaria transmission are being developed. The sterile insect technique involves the introduction of specific genes into a wild vector population through mating; it has so far only proven its efficacy on a limited experimental scale[203, 204]. A more recent development is the genetic modification of the ability of the natural vector population to transmit the malaria parasite[205]. Both developments are impeded by similar technical and human resource shortcomings[206], as well as uncertainties surrounding ethical and safety issues[207]. Nevertheless, technological developments have been a cause for optimism about the potential for genetic methods as public health tools[208].

3.2.10 Botanicals

The traditional burning of local plants and leaves is commonly used for its mosquito repellent effect; an alternative method is the placement of repellent plants near or in houses. Their local availability and cheap production make them attractive options to reduce human exposure to malaria, particularly in combination with ITN[209, 210]. Botanical products are occasionally used as larvicides. Particularly, products of the neem tree (*Azadirachta indica*) have shown good potential for larval control, are low-cost, readily available in many areas and are relatively safe, but the effects on non-target organisms requires further study[211, 212].

3.2.11 Polystyrene beads

Expanded polystyrene beads have been used to control vector breeding in small confined water collections, for example in borrow pits, wells or small water tanks[213]. A thin layer prevents egg deposition and causes suffocation of mosquito larvae present in the water. A study in gem pits in Sri Lanka showed that polystyrene beads were efficacious in controlling malaria vector breeding of the malaria vector, but less cost-effective than insect growth regulators[160].

3.2.12 Zooprophylaxis

Zooprophylaxis refers to the control of vector-borne diseases by attracting vectors to domestic animals in which the pathogen cannot amplify[214]. In areas where malaria vectors have a strong preference to feed on livestock rather than on humans, the spatial planning of livestock management can, in theory, reduce malaria transmission in humans. However, the presence of livestock near human habitation can also enhance malaria transmission[215].

Conclusion: Non-chemical methods have clearly contributed to successful malaria control. More work is needed to study their effectiveness as main or supplementary interventions at programme level. A number of promising technologies are under development.

3.3 Cost and cost-effectiveness of alternatives

3.3.1 Indoor residual spraying and insecticide-treated bed nets

A prevention strategy is more costly than treatment[216], because it targets the entire population or a sub-population aiming to reduce malaria risk. Nonetheless, preventive interventions contribute an important part of the achievable benefits in malaria control[217]. Most studies on cost-effectiveness analysis of malaria prevention have concentrated on ITN and IRS. Both intervention methods have been considered attractive options (in terms of cost per DALY averted) in low and middle income countries[22]. The relative effectiveness of ITN and IRS is roughly comparable, but depends on vector behaviour and human sleeping habits in a given setting[29, 218-220]. A study in western India reported a higher effectiveness for ITN than for IRS[221]. Most studies found ITN to be the less costly option, others reported IRS as the cheapest[218, 222-224]. As a general comparison, it has recently been estimated that the annual cost of protecting people is more than three times lower for LLIN that for IRS[225]. In epidemic-prone areas, IRS is likely to be most responsive to signs of malaria outbreaks[220].

3.3.2 Other methods

There is a lack of data on the cost-effectiveness of alternative interventions and strategies. Their effectiveness depends significantly on the ecological and epidemiological situation locally. A thorough cost-effectiveness analysis of malaria control in the Zambia copper belt in the 1930s and 1940s indicated that environmental management was as cost effective as ITN[226]. Within three to five years, malaria morbidity and mortality were reduced by 70-95%. Environmental management can benefit from local resources, reducing the need for external funds. Recent trials on the use of microbial larvicides for malaria control showed that significant reductions in larval abundance and a 92% reduced biting rate was achieved at US$ 0.90 per person per year, but effects on malaria morbidity remain to be studied[194]. Other studies indicated high cost-effectiveness of insecticide sponging of livestock[165] and the use of repellent plants as low-cost means of household protection for incorporation in IVM programmes[209].

Conclusion: Cost-effective methods for malaria control include IRS, ITN and non-chemical methods, but information on the latter is scant and depends significantly on the local context.

3.4 Current implementation of alternatives to DDT

The past decade has seen a steady increase in commitment to malaria control by affected countries and the international community. This has caused a massive boost in financial and human resources available for implementation of vector control interventions, due to the support of organizations such as the Global Fund, the World Bank, the United States President's Malaria Initiative and many non-governmental organizations. Recently, targets have been set for elimination of malaria[152, 227, 228]. Main vector control interventions being implemented are ITN and, increasingly, IRS.

3.4.1 Insecticide-treated bed nets

Different strategies exist for delivery and scaling-up of ITN, using free distribution, integration with other public health intervention campaigns, commercialized and social marketing approaches[224, 229-231]. There is now reasonable consensus that a diversity of delivery approaches is optimal in most situations[143, 232, 233]. Targets have been set for the coverage of affected populations with ITN[217, 234, 235]. National campaigns of free or highly-subsidized ITN have reportedly approached coverage levels of 50% or higher among households in Ethiopia, Eritrea, Guinea Bissau, Mali, Niger, Zambia, Togo, Malawi, Rwanda, Zanzibar and Kenya [225, 234, 236-238], resulting in a dramatic reduction in malaria incidence.

3.4.2 Indoor residual spraying

Most malaria-affected countries outside the African region are reducing or abandoning the use of IRS – changing to ITN or a combination of ITN and larval control methods. In China, Vietnam and the Solomon Islands, ITN has largely replaced IRS[130]. Conversely, the use of IRS is on the increase in Africa, where it has been more difficult to come to grips with the malaria situation due to aspects of vector biology and disease epidemiology. IRS in Africa is being stimulated in large part by the US President's Malaria Initiative[239]. Some countries plan to expand their IRS programmes into areas of high transmission, and several countries are initiating pilot programmes to re-introduce IRS as a vector control intervention. In South Asia, indoor spraying using DDT and alternative insecticides continues on a large scale. In India, it was reported that the average coverage of targeted houses with IRS was 53%, but only 16% of treated houses had uniform and complete spraying while spray equipment was found to be of poor quality[240]; this indicates that the quality of the intervention is a critical issue.

3.4.3 Other chemical methods

Despite its relative high risk of exposure to humans and the environment, space spraying aiming to kill adult vectors is used by some countries, particularly in the Americas, as a malaria control intervention but without clear evidence of its epidemiological impact. As a crude comparison, the reported global consumption of insecticides for space spraying is approximately one eighth of that reported for IRS (figures from India and China were missing)[241]. Reported use of chemicals as larvicides for malaria control is relatively small, amounting to roughly 3% of the consumption for IRS[241]. Larval control is more common in urban areas, where breeding sites are human made. Several countries have reported a small-scale use of insect growth regulators and bacterial insecticides for malaria larval control. In several other countries these methods are currently tested on a pilot scale.

3.4.4 Non-chemical methods

Source reduction, flushing of canals, intermittent irrigation and biological control have often been promoted or tested in pilot projects as non-chemical methods of vector control. However, contemporary cases of sustained implementation are not common. Some examples are given here. In irrigated rice in China, reductions in vector densities and malaria incidence has been attributed to the large-scale application of intermittent irrigation[242]. In Oaxaca, Mexico, training of volunteers and mobilization of community members to clean streambeds and eliminate green algae on a monthly basis over a three-year period combined with focal IRS resulted in an 80% reduction of the local vector[243]. In the 1980s in an area of low malaria endemicity in Gujarat, India, a strategy using engineering, elimination of vector breeding sites, use of larvivorous fish, chemotherapy, community participation, health education and income generation caused a reduction in the morbidity of malaria at a cost-effectiveness roughly comparable to IRS[244, 245]. The current application of larvivorous fish is widespread in Gujarat and patchy in other parts of India[240]. In Sri Lanka a water management regime has been implemented in a natural stream to reduce the number of breeding sites of the main malaria vector downstream[173, 174]. Also in Sri Lanka, an inter-sector approach to educating rice farmers about environmental management options in connection with improvement of agricultural pest management resulted in reduced populations of anophelines and reduced insecticide use in agriculture[170, 171]. Several ongoing or planned projects aim to demonstrate the effectiveness of alternatives to DDT in different regions, with sponsorship by the Global Environment Facility[36].

Conclusion: The implementation of ITN and IRS has seen a dramatic increase in the past decade, especially in Africa. These tools depend chiefly on the effect of pyrethroids and DDT, while the evidence base on non-chemical tools and integrated strategies needs urgent strengthening.

3.5 Barriers, gaps and solutions

3.5.1 Insecticide resistance

Resistance of vectors to insecticides is a direct threat to the sustainability of the two main malaria prevention methods, ITN and IRS, as demonstrated in South Africa with the recent emergence of pyrethroid resistance in *Anopheles funestus*[131, 246]. Pyrethroid resistance in malaria vectors has been reported from West, East and southern Africa[93, 94, 247], involving several resistance mechanisms. This has implications for both ITN and IRS. *Kdr*-type resistance in *An. gambiae* is developing in large parts of West and Central Africa, and has been associated with the extensive use of pyrethroids in agriculture[88, 89]. Organophosphate and carbamate resistance in malaria vectors has been reported from a few sites[94]; in India resistance to malathion was attributed to use in agriculture[248]. The number of insecticides available for use in vector control is limited[121, 122], and new insecticides are emerging at a slow pace.

There is growing concern about sustained effectiveness of ITN, because the intervention currently depends solely on pyrethroid insecticides[249, 250]. Multi-village studies in an area with highly resistant *An. gambiae* in Côte d'Ivoire indicated that ITN retained most of its effect[251, 252]. As explanation was offered that resistant mosquitoes were less irritated which resulted in a higher uptake of insecticide. More worrisome are the results of a recent semi-field study from an area with highly resistant vectors in Benin[253], showing a major loss in efficacy of ITN locally. The possible role of an additional metabolic resistance mechanism in the vector population at the site in Benin needs further investigation[254, 255]. In addition, observations over the past 10 years in Uganda have indicated a gradual development of resistance against pyrethroids used in ITN[256]. Without the insecticidal action, bed nets provide a much lower level of personal protection[140].

Causes of resistance are the selection pressure from, both, insecticide use in agriculture and in public health (i.e. ITN or IRS programmes). The latter would apply especially to situations of high programme coverage, with strong preference of the vector to feed on humans or to rest indoors, and with a substantial killing effect on vector populations. There are indications of increased frequency of resistance genes attributable to IRS or ITN programmes[257-259]. Moreover, there are records of a change in behaviour from indoor resting to outdoor resting in response to indoor spraying, and a change in daily pattern of biting and host choice in response to ITN interventions[127, 260-262].

Long-term solutions to the problem of resistance involve integrated strategies with actions aiming to reduce the selection pressure thus preventing or delaying resistance development, and aiming to reduce dependency on chemical insecticides for vector control. Short- or medium-term solutions are the development of improved insecticides or formulations and an efficient support system for monitoring and decision-making regarding insecticide choice and resistance management. A system of sentinel sites to monitor vector density, quantify insecticide resistance and guide informed decision-making on insecticide choice still needs to be established in most disease endemic countries[125, 263, 264]. A new independent report from India pointed out that, in practice, the insecticide choice for IRS is rarely based on contemporary insecticide susceptibility testing[240]. The African Network for Vector Resistance to Insecticides was founded in 2000 to build the capacity of African countries for the testing, monitoring and management of insecticide resistance, to harmonize methodologies, and to fill some of the information gaps on vector resistance in the region[93, 94]. International vector resistance networks are absent in other regions. Further, research is needed on the relative value of repellent, irritant and toxic actions of insecticides in relation to vector control, transmission reduction and resistance management[113]. This could lead to products with an optimal mix of actions tailored to the intervention method and to the objectives and timeline of malaria control.

3.5.2 Operational capacity

The effective coverage of programmes depends critically on the access and targeting of populations and vulnerable groups most at risk of malaria, the degree of correct compliance of the provider and adherence to the intervention by the consumer. In most countries with endemic malaria, the reality is that insufficient capacity exists within health systems to plan and implement programmes effectively.

In many malaria-affected countries, reforms in the health sector have lead to the decentralization of planning and budgeting. Consequently, the responsibility for service provision has been shifted from national to sub-national or district-level health departments, requiring new skills and human resources specific to malaria vector control at each level. An analysis of four malaria success stories suggested the potential benefit of decentralization[265]. In selected countries, it was found that technical staff and programmatic capacity available at sub-national or district level – but supported by national capacity – and the use of multiple interventions contributed to an improvement of malaria control compared to the baseline with vertical programmes. In most other countries, however, there has been a lack of guidance on how malaria control might be implemented in a decentralized environment[266]. This has lead to inadequate technical and programmatic capacity at lower administrative levels and insufficient priority given to malaria in local allocation of resources by the health sector, thus hampering effective implementation of vector control programmes. Still, many donor-funded programmes are being implemented in a vertical manner, not by design strengthening the health systems at district or sub-district level and, consequently, the specialist capacity and skills are inadequate at these levels.

Traditionally, IRS has been managed as vertical programmes by the health sector, and this is still the case in a number of countries. There are also examples of programmes by the private sector[33]. In several countries, however, the transition process following health reforms has caused an erosion of the specialist skills and human resources as illustrated in the case of Zimbabwe[267]. In contrast with IRS, ITN has used a variety of delivery models (including vertical programmes, integrated programmes, the private sector, non-governmental organizations and communities), and have been integrated with other health sector programmes[232, 268, 269]. As the global thrust is to promote coverage with the two most important interventions – ITNs and IRS, vector control capacity is needed at the appropriate levels, by recruitment, training and deployment of local personnel.

With regard to methods other than IRS and ITN, particularly non-chemical methods, capacity in all countries needs to be developed or further strengthened in view of reducing the almost exclusive reliance on chemical insecticides for vector control in the near future. Interventions involving environmental management and other larval control methods clearly require the participation of other sectors and communities. Implementing and enabling these interventions has been reported as successful in decentralized programmes[265], but requires closer study. It has further been suggested that environmental management should be integrated with other development efforts[270].

3.5.3 Inter-sector action

Engaging other public sectors in vector control activities was the norm during the pre-DDT era, and revived to some extent in the wake of the Alma Ata Declaration on Primary Health Care. Inter-sector action for health is one of the original pillars of the Health for All movement. Many decisions affecting the environmental receptivity and community vulnerability to vector borne diseases are taken in other public sectors, e.g. planning and implementation of irrigation schemes and dams, urban infrastructure development and operation. A project’s implications for vector-borne disease need to be considered at the onset. However, there is insufficient awareness outside the health sector of the economic implications of the malaria burden, while sectors are under increasing pressure to deliver progress in their own area against increasing costs. Any initiative to promote inter-sector action for vector control will require simultaneous complementary action of awareness creation through advocacy, a strengthening of the evidence base that actions by other sectors contribute importantly and sustainably to vector control goals, training of decision makers in inter-sector negotiation and, most importantly, the creation of a policy framework conducive to inter-sector collaboration.

3.5.4 Community participation

Community participation comes in a variety of forms[271]. Every vector control method requires a certain level of community participation. Effective IRS depends on the acceptance and adherence by household members. ITN requires proper maintenance and use of nets by those most at risk. Environmental management and other larval control methods often rely on active community participation in planning and implementation of control action. Two stages in community participation can be distinguished in the context of vector control: (i) knowledge and skills acquired and (ii) the resulting behavioural change and vector control action. Regarding the former, educational programmes and 'information, education and communication' initiatives are essential in preparing communities for their role in disease prevention and to motivate them into action[234, 272, 273]. This aspect has previously been undervalued in programmes on ITN and IRS but could serve as an extension of health services in the control of vector-borne disease. Practical education and skill development is particularly important for vector control methods that require a basic level of ecological understanding and hands-on action[274]. For example, environmental methods have to be tailored to contextual conditions; consequently, it is central to engage the community in the decision-making at every opportunity[270, 275].

Lack of economic incentives is a barrier for achieving active and sustained participation of communities[245]. Lack of capacity to facilitate community participation and education is another constraint. A possible solution is the integration of health activities with programmes that generate income or raise agricultural productivity. In this context, the demonstration project on a bio-environmental strategy for vector control in Gujarat, India, provides an important example[244]. Rich experience with successful participatory approaches exists within the agriculture sector[276]; the health sector potentially benefits from these resources by adopting integrated approaches and building inter-sector linkages[245]. One relevant model is the Farmer Field School in Integrated Pest Management developed and promoted by the FAO. This model has recently been successfully used in Sri Lanka for achieving active community participation for the dual purpose of agricultural pest management and disease vector control[171].

3.5.5 Research and development

The current focus of research in relation to DDT alternatives is on alternative chemical insecticide products for ITN and IRS which pose less risk to human health and the environment. However, there is need to broaden the scope of innovative research, with increased emphasis given to technologies and strategies that reduce the reliance on chemical insecticides, in line with World Health Assembly-resolution WHA-50.13. Moreover, operational research is needed to study the effectiveness and cost-effectiveness of integrated strategies combining different interventions for malaria vector control. Large interdisciplinary research and training programs must be promoted, especially in Africa, emphasizing integrated control technologies and strategies, fostering regional collaboration, and supporting research career development[277]. Donors should use some leverage to encourage government ministries to develop career opportunities for the mid-level scientifically trained personnel involved in the organization, implementation and evaluation of disease control operations so that the programmes can be sustained.

3.5.6 Funding support

Major investment is needed to support the fragile status of health systems, particularly in Sub-Saharan Africa. Moreover, in order to achieve coverage of targeted populations with effective alternatives to DDT requires increased assistance from external donors in the years to come. Finally, research and research capacity on innovative technologies and integrated approaches clearly need increased commitment and investment.

Conclusion: Important barriers and gaps in the development and implementation of DDT alternatives are insecticide resistance, operational capacity, community participation, research & development and funding support. A common solution is the support for long-term, integrated and multi-partner strategies of vector control.

4. Integrated Vector Management

4.1 Integration of methods

With the global malaria eradication campaign, the ecological approach to vector control of preceding years was largely exchanged for indoor residual spraying while larval control through environmental management and biological methods was ignored[115]. Consequently, the focus on the adult stage of the vector and on pathogen transmission caused an erosion of the ecological basis for vector control[278-280].

An integrated approach to malaria control, and vector control in particular, has frequently been advocated[265, 267, 278, 280-283]. A broadened scope of malaria control would cover a wider set of determinants of disease[168, 284, 285], some outside the working domain of the health sector thus calling for inter-sector collaboration. Various studies have demonstrated that integration and localized targeting of vector control methods resulted in significant reductions in transmission and morbidity rates of malaria[188-190, 226, 243, 286]. Moreover, modelling studies predicted that combinations of interventions can be much more effective in reducing malaria transmission than individual interventions, and that the effect of IRS and

ITN is amplified by environmental management, even in areas of intense transmission [279, 287]. Now that levels of transmission and prevalence of malaria are clearly decreasing in a number of African countries following recent intensive control efforts[143, 225, 288-291], there is a greater prospective scope for incorporating environmental management and other non-chemical methods in strategies to achieve further reductions in malaria transmission and to increase sustainability of control efforts.

Besides its direct effect on transmission intensity, the integration of methods is also expected to contribute to resistance management. For example, larval control is expected to prevent or delay the onset of vector resistance to insecticides used for ITN or IRS[187], while measures that reduce human contact with vectors – for example through their proximity, housing conditions or presence of repellent plants – are expected to reduce the selection for resistance. Studies have furthermore suggested the additional benefit of transmission control in slowing down the spread and prevalence of drug resistance in high transmission areas[292, 293].

Conclusion: The value of integration of vector control methods for malaria control is generally recognized.

4.2 IVM framework

The need for a reduced reliance on insecticides for vector-borne control through promotion of integrated-pest-management approaches, pointed out in World Health Assembly-resolution WHA-50.13, has been stressed further in the recommendations by the Intergovernmental Forum on Chemical Safety, Forum VI. In practice, however, malaria vector control is conducted predominantly and increasingly by insecticidal methods. As discussed above, the efficacy of ITN is already being affected by the development of insecticide resistance in certain locations, and currently expanding operations of IRS are running the same risk. In the past, some IRS operations were time-limited because the level of investment required and the susceptibility in the vector population could not be sustained.

IVM is seen as a way forward to improve cost-effectiveness, ecological soundness and sustainability of disease vector control[12, 294]. Modelled on the positive experience from Integrated Pest Management in agriculture, IVM has been defined as “a rational decision-making process for the optimal use of resources for vector control”[13]. It foresees decision-making at the lowest possible level in accordance with local mapping and situational analysis, and it often depends on inter-sector action and community participation. IVM still is an evolving field. Guidelines and work plans have been made for the implementation of national IVM programmes in Africa and Asia[295-298]. National action plans and project proposals on vector management are currently being developed in a number of countries and regions, under the auspices of the Stockholm Convention, in collaboration with the WHO and with funding from the Global Environment Facility[36].

There are different possible interpretations of IVM in practice. Some view IVM as an approach to centralized targeting and execution of single interventions or tailor-made ‘packages’ based on epidemiological profiles and transmission rates. Others may stress the need for decentralized mapping and decision-making, or the active role of other sectors or communities in vector control. Clearly, criteria for the implementation of IVM need to be further developed and consolidated. Decentralization in the health sector can be expected to favour IVM by facilitating situational analysis and tailored action at the local level. Local assessment and decision-making can address variations in malaria epidemiology at a small spatial scale, and has potential to involve communities and thus address disease determinants that relate to their own actions and conditions[275]. Further work is needed to test this decentralized approach.

The global action plan of the Roll Back Malaria Partnership involves the scaling-up of the two main vector control interventions, ITN and IRS, for an immediate impact on the malaria burden of populations at risk[152]. However, to address sustainability issues, it is critical that these interventions are implemented in the context of an IVM approach, by prioritizing decision-making based on local evidence of disease epidemiology, vector ecology and vector susceptibility, and by integrating all available resources and methods in an effective and ecologically sound manner. This approach is needed to achieve maximum and sustainable impact on malaria, or to achieve elimination objectives. The IVM approach aims to provide a long-term strategy for vector control, transmission reduction and resistance management that is not carried solely by malaria control programmes and their limited budgets, but that is integrated with other arms of public health and other sectors, thus extending the institutional basis for malaria prevention by building broader alliances and enhancing local capacity and ownership.

Conclusion: IVM provides a framework for developing and implementing effective technologies and strategies as sustainable alternatives to DDT.

4.3 Stakeholders and partnership

There are a number of potential stakeholders in the development and implementation of innovative technologies and IVM strategies as alternatives to DDT. They include malaria-endemic country governments, non-governmental organizations, inter-governmental organizations (WHO, UNEP, FAO, UNDP, World Bank, Secretariat of the Stockholm Convention), international funding agencies, foundations, bilateral donors, academia and research, and the private sector. In addition, a number of relevant public-private partnerships are the Roll Back Malaria Partnership; the Innovative Vector Control Consortium (funded by the Bill and Melinda Gates Foundation); the Multilateral Initiative on Malaria; and the Special Programme for Research and Training in Tropical Diseases. Ever since the era of the malaria eradication campaign, vector control in many countries suffered from fragmented and inconsistent efforts maximizing short-term returns for a given (limited) budget, often by-passing the established systems and available structures. Also, the use of chemical treatments has been propagated as the principal and acceptable way of controlling disease, while there has been little support for alternatives such as environmental management[168].

The dual objectives of the Stockholm Convention and the Global Malaria Program – with regard to restricting the use of DDT and tackling malaria – demand a concerted effort by the stakeholders that prioritizes an integrated and sustainable approach to vector management. A business plan for a global partnership to develop alternatives to DDT is therefore urgently needed. A business plan would: (1) provide a long-term vision, mission and strategy on vector and disease management for all stakeholders; (2) outline a mechanism for harmonized development, implementation and evaluation activities; and (3) ensure long-term financial and political commitment.

Conclusion: To achieve a concerted effort by all stakeholders, a business plan for a global partnership on vector management is needed.

5. Conclusions and recommendations

5.1 Conclusions

The reported global use of DDT for disease vector control is 4-5000 t per year, with India consistently as the largest consumer and a number of countries re-introducing DDT. The effectiveness of DDT depends on local settings and merits closer consideration vis-à-vis chemical and non-chemical alternative products, methods and strategies. Legislation and capacity to enforce regulations and good use and management practice, specifically for DDT, is inadequate in most countries. Donors aiding in the purchase of DDT should have accountability to report to WHO or UNEP. In many countries the monitoring and management of DDT stocks urgently needs to be strengthened, e.g. by involving the Environment Sector. A global reporting system on use of DDT is in place but thus far the response rate has been low.

Indoor spraying of DDT for vector control has shown to cause high levels of human exposure. This could adversely affect human health, as the evidence base on some of the more serious and chronic health effects of DDT is growing. Moreover, the occurrence of resistance in malaria vectors to the toxic action of DDT is common and appears to be spreading. The spectre of DDT being illegally used outside the health sector raises concern about environmental pollution in export crops, while the environmental fate of DDT applied in IRS remains to be studied.

As immediate alternatives to DDT, effective chemical methods for vector control and personal protection are available, but the arsenal of insecticides is limited. Alternative insecticides should pose less risk to human health and the environment and be supported with monitoring data. The coverage of populations with insecticide-treated bed nets and indoor residual spraying has seen a substantial increase in recent years, especially in Africa. However, in certain areas the development of insecticide resistance is reducing the efficacy of these methods. Insecticides with novel chemistry will not come to market in the short term. To be prepared for disease emergencies in the future, the continued effectiveness of insecticides needs to be safeguarded.

A number of non-chemical methods have proven their value in malaria control in certain settings but testing of their effectiveness and cost-effectiveness as main or supplementary intervention has not been given due emphasis in field programmes. Several new technologies are under development but require increased investment and need to be subjected to health risk assessment. The development of alternatives to DDT in the control of leishmaniasis in India also needs investment, considering the reported amounts of DDT used[299].

Important barriers and gaps in the development and implementation of chemical and non-chemical alternatives to DDT are the development of insecticide resistance; limited operational capacity; limited inter-sector action; little support for and experience with community participation within the heath sector; insufficient priority given to innovative research and operational research; and a major shortage in funding support for integrated approaches. Some of these barriers also apply to the use of DDT.

A common solution is the support for long-term, integrated and multi-partner strategies of vector control and the continued development of new technologies, particularly those that do not rely on chemical insecticides. Integrated Vector Management (IVM), defined as “a rational decision-making process for the optimal use of resources for vector control” is seen as a promising way forward to improve cost-effectiveness, ecological soundness and sustainability of vector control. IVM has potential to reduce transmission intensity and prevent resistance development while reducing the sole reliance on insecticides.

The strategy of the Roll Back Malaria Partnership involves the scaling up of ITN and IRS for an immediate impact on the malaria burden[152]. However, it is essential that these interventions are implemented in the context of an IVM strategy, by being evidence-based, and by integrating all available resources and methods in a cost-effective and ecologically sound manner. Indeed, now that levels of transmission and prevalence of malaria are considerably decreasing in a number of African countries following recent intensive control efforts, there is a greater prospective role for incorporating non-chemical methods in IVM strategies to achieve further reductions in malaria transmission. This will increase the sustainability of control efforts and assist in achieving malaria elimination objectives.

The dual objectives of the Stockholm Convention and the Global Malaria Program – with regard to restricting the use of DDT and tackling malaria – demand a concerted effort by the stakeholders that prioritizes an integrated and sustainable approach to vector management. A business plan for a global partnership to develop alternatives to DDT is therefore urgently needed.

5.2 Recommendations

i. External financial support for long-term, integrated and multi-partner strategies of malaria vector control is urgently needed;
ii. In the short term, immediate alternatives to DDT need to be accepted by donors and emphasized for implementation;
iii. Promising innovative technologies, particularly those that do not rely on chemical insecticides, need more emphasis in research and development;
iv. As the evidence base on some of the more serious and chronic health effects is mounting, the assessment of health risks of DDT needs to be re-visited and a system for monitoring exposure from IRS established;
v. Criteria for implementation of IVM need to be further developed and consolidated;
vi. A business plan for a global partnership to develop alternatives to DDT is needed.

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