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Original Article

Use, Disposal and Environmental Challenges of Insecticide Treated Nets

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ABSTRACT

Insecticide treated nets are critical tools for prevention of malaria and other mosquito-borne diseases. They have also been demonstrated to prevent nuisance and infective bites from a few other insects. Recently, there has been an increased push by the international community to eliminate malaria and therefore resources have been channelled into higher production and supply of ITNs to endemic areas, thus increasing their presence in the environment. The trend is unlikely to change given that ITNS are still strongly recommended by WHO as part of the methods with which significant reduction in malaria incidence can be achieved. ITNS are available in different physical properties and chemical treatments. Differences in physico-chemical properties do not only confer different abilities of insect bite protection, but they also determine the extent of environmental degradation caused especially when proper disposal guidelines are not followed. Environmental pollution may pose human health risks as well as affecting susceptible organisms within vulnerable ecosystems. Owing to the undesirable effects of treated net associated environmental pollution, there is increasing advocacy for and research in the improvement of these important tools to standards of degradable materials and natural chemicals with little or no effect to the environment. This paper reviews the bednet properties, their use and misuse, disposal and environmental pollution that arises from their misuse and incorrect disposal. To do this, Dimensions scientific research database was queried using predetermined and appropriate search words. Recommendations for changes of materials and chemical treatments are provided.

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INTRODUCTION

Insecticide treated nets play a major role as part of malaria control toolkit in endemic countries. They remain effective and WHO encourages their continued use to prevent malaria (WHO, 2022). They are also efficient in preventing sand fly blood feeding on humans (Ikon & Ejezie, 2003). Insecticide treated bednets work by creating a physical barrier between humans and mosquitoes, killing, or knocking down susceptible mosquitoes due to the insecticide in the netting material and eliciting repellence effects on vectors (CDC, 2019). Whereas numerous studies and reviews are dedicated to their efficacy, physical and chemical integrity, availability, supply and distribution channels, coverage, and use behaviour, there are limited reviews on treated nets' misuse, accidental contact of insecticides, disposal, and environmental degradation (Okumu& moore, 2011; Kasili & Mwangangi, 2016; Kaur et al., 2021; Mboma et al., 2021; Nyangi et al., 2021; Fru et al., 2021). . A recent article considered seventeen studies to model the interplay between malaria dynamics, human intoxication, and ecosystem damage and levels of usage (Gutiérrez-Jara, Vogt-Geisse & Cabrera, 2022). The main concern of the article was human contamination through contact of bednets and the likely consumption of fish which may have bioaccumulated chemicals because of treated bednet use as fishing nets. However, a broader spectrum of environmental pollution resulting from bednet use and disposal need to be reviewed.

To achieve this goal, Dimensions scientific research database was queried with the following search terms: "treated bednets AND environmental pollution", "Bednet misuse", "ITN repurposing" and LLINs AND environmental pollution. Searches were limited to between the year 2000 and current outputs.

Bednet Physico-Chemical Characteristics

Bednets come in a variety of sizes, shapes, colours, materials, and insecticide treatments to suit user preference and disease transmission dynamics. The materials commonly used for the nets vary from polyester to composites of high-density polyethylene and low-density polyethylene (CDC, 2019). There are monofilament and multifilament nets. Monofilament nets have one extruded strand knitted into a net while multifilament ones have many fibres included in one strand. These processes contribute to the bursting strength which is directly related to the net physical integrity (Skovmand & Bosselmann, 2011). The fibres are knitted with rhomboid or hexagonal holes thereby forming a mesh of different hole sizes: 8.7 holes/cm2 for polyethylene and 24 holes/cm2 for polyester.

Initially Insecticide (ITNs) treated nets were simply dipped into the insecticide solution and then dried in the shade. Long lasting insecticidal nets (LLINs) are coated using technology that involves an insecticidal resin that binds to the surface of the net while others are incorporated with the insecticide during fibre formation (Brake et al., 2022). Pyrethroids and Pyrroles are currently the only classes of insecticide recommended for use on ITNs due to their perceived low mammalian toxicity and

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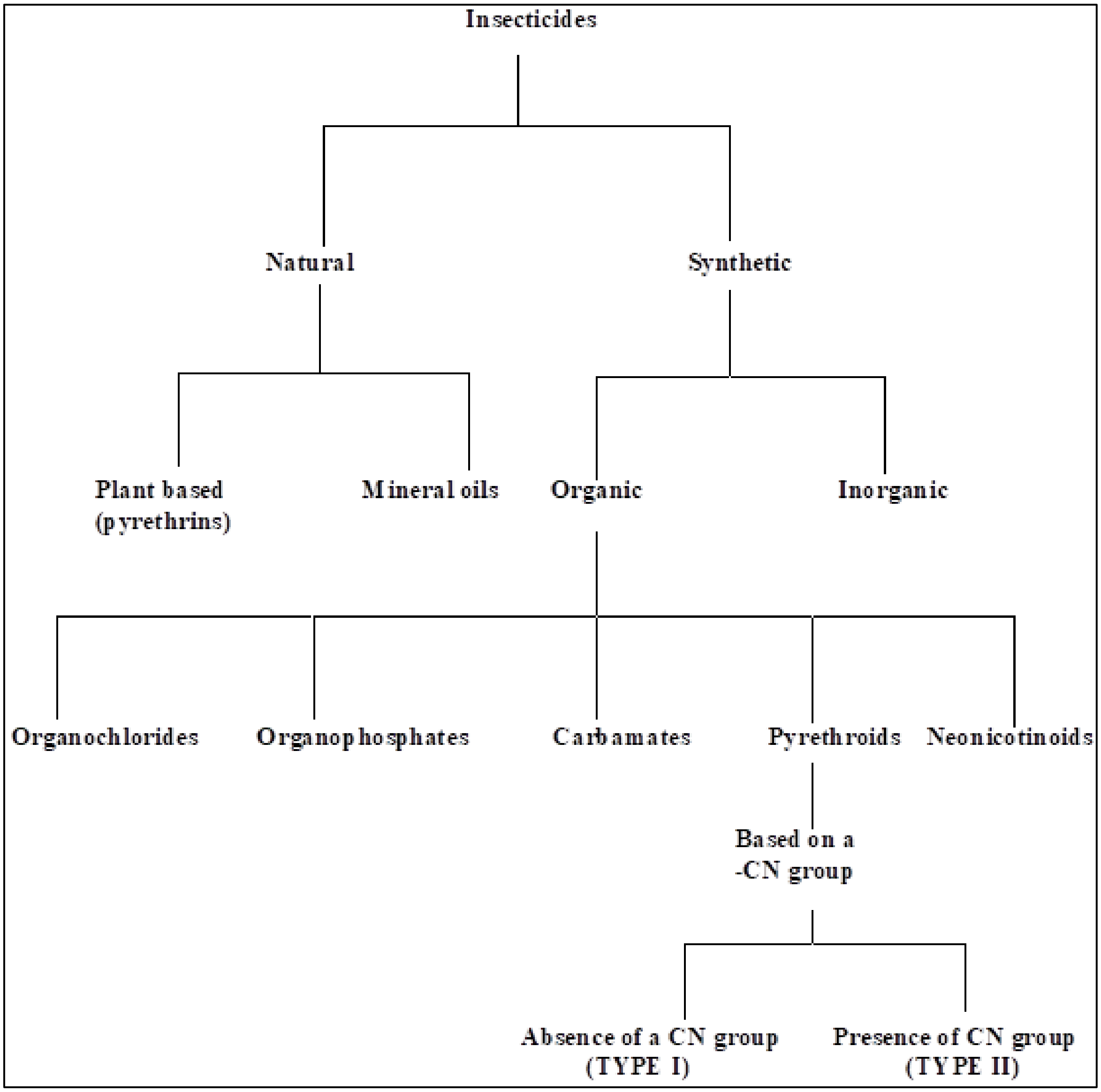
long residual activity (Hougard et al., 2003; CDC, 2019).

Pyrethroid is a class of inorganic insecticides. *Figure 1* shows a summary of common insecticides classification specifically zeroing in on pyrethroids.

Figure 1: General classification of insecticides



They are synthetics of pyrethrins that naturally occur in *Chrysanthemum spp* flowers. Pyrethrins are a mixture of six chemicals Shown in *Figure 2*.

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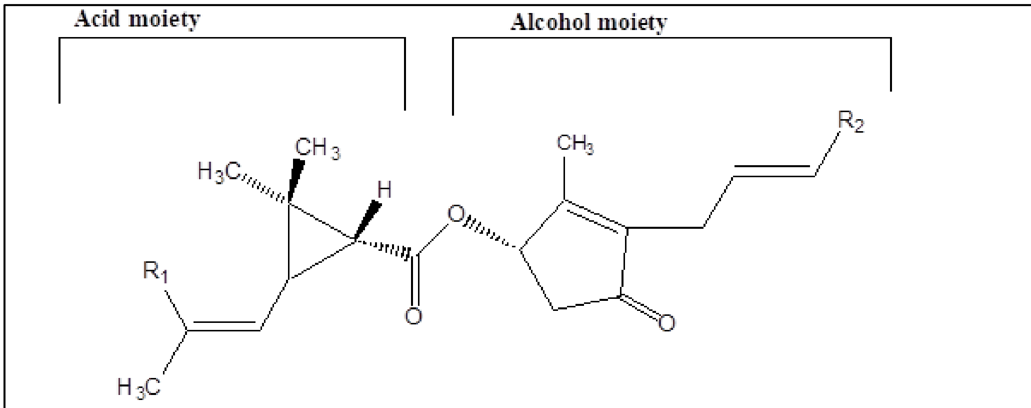
Figure 2: The chemical structures of the six constituents from pyrethrum extracts which are collectively known as pyrethrins



Esters of Chrysanthemic acid	R_1	R_2	Esters of Pyrethric acid	R_1	R_2
Pyrethrin I	$-CH_3$	$-CHCH_2$	Pyrethrin II	$CH_3OC(O)-$	$-CHCH_2$
Cinerin I	$-CH_3$	$-CH_3$	Cinerin II	$CH_3OC(O)-$	$-CH_3$
Jasmolin I	$-CH_3$	$-CH_2CH_3$	Jasmolin II	$CH_3OC(O)-$	$-CH_2CH_3$

Pyrethroids are however longer lasting than pyrethrins (Ravula & Yenugu, 2021). There are far more than seventeen different pyrethroids based on presence or absence of cyano groups as part of the molecule synthesized but similar in structure to pyrethrins (Chrustek et al., 2018). The initial pyrethroids used in impregnation of nets were mainly permethrin and deltamethrin. These two belong to different groups of pyrethroids as shown in *Figures 3* and *4*.

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Figure 3: Synthetic pyrethroids that do not contain cyano (nitrile) or amine groups (Type I)

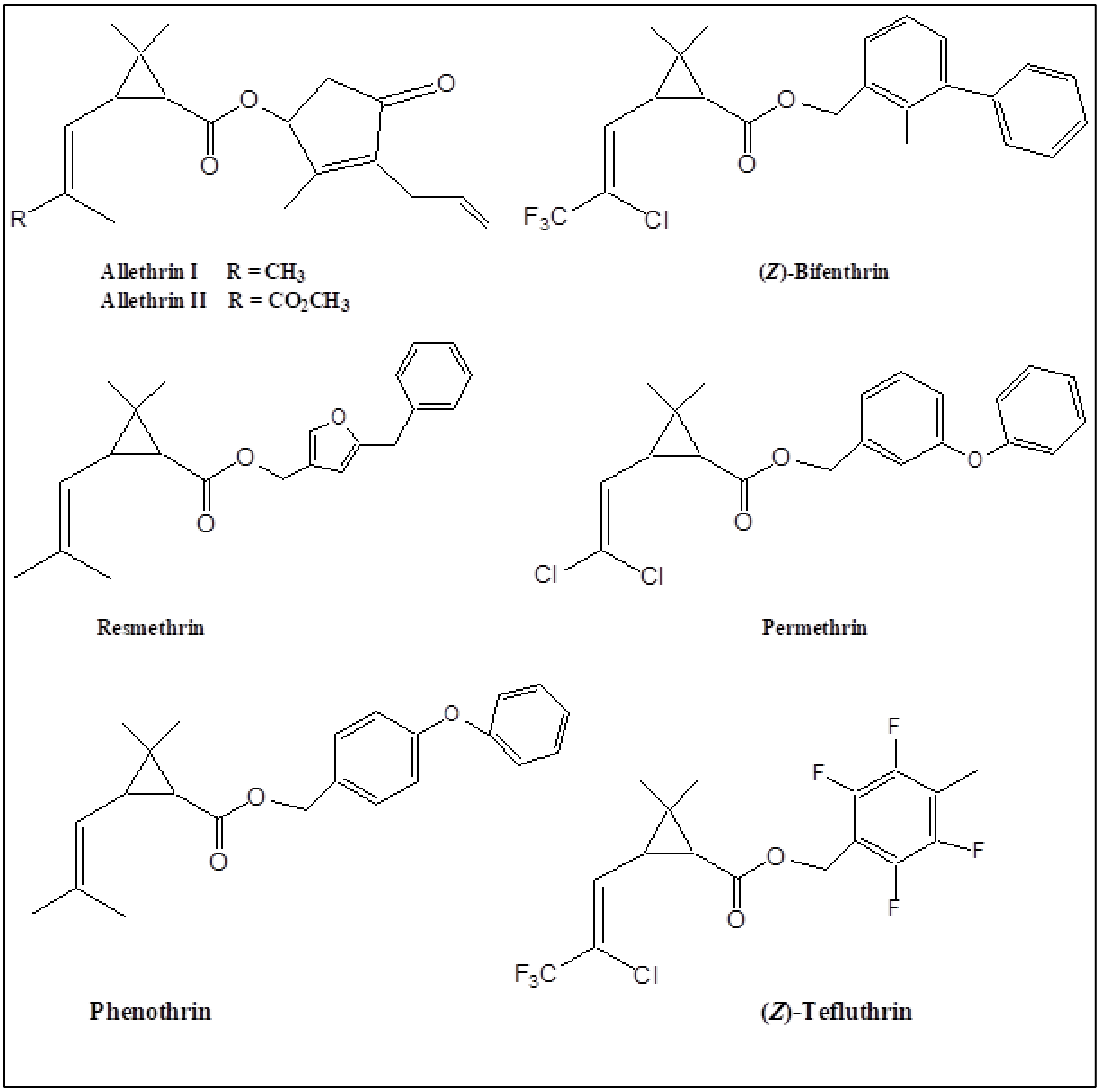

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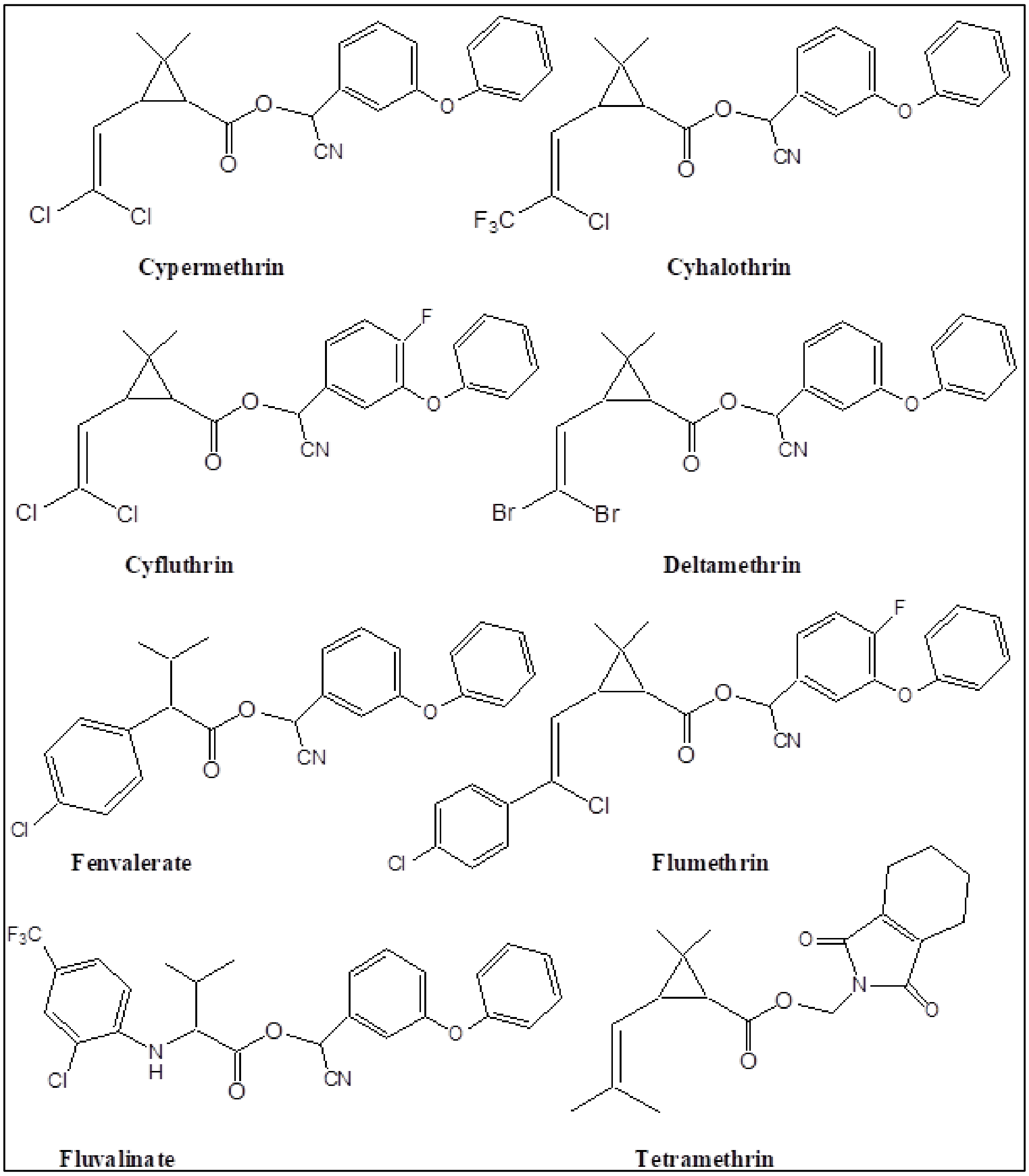
Figure 4: Synthetic pyrethroids that contain cyano (nitrile) or amine groups (Type II)



Alpha-cyano group in type II synthetic pyrethroids renders them more neurotoxic than their non-cyano type I counterparts.

Since 2015, bednets treated with pyrethroids have not been efficient on their own resulting in stalling of reduction of malaria burden (Tungu et al., 2021). A continued search led to a new insecticide. Chlorfenypyr is the new non-pyrethroid insecticide whose mixture with a pyrethroid alpha-cypermethrin has proved efficacious against pyrethroid resistant mosquitoes in experimental huts (Tungu et al., 2021). Chlorfenapyr, the active ingredient alongside alpha-cypermethrin in Interceptor® G2 (BASF, Ludwigshafen Germany), is a slow acting toxin that interferes with respiratory pathways and proton gradients (Agumba et al., 2019). It is a pro-insecticide (meaning it is metabolized into an active insecticide after entering the host), initially used for termite control and crop protection against several insects and mite pests. It is derived from a class of microbially produced compounds known as halogenated pyrroles.

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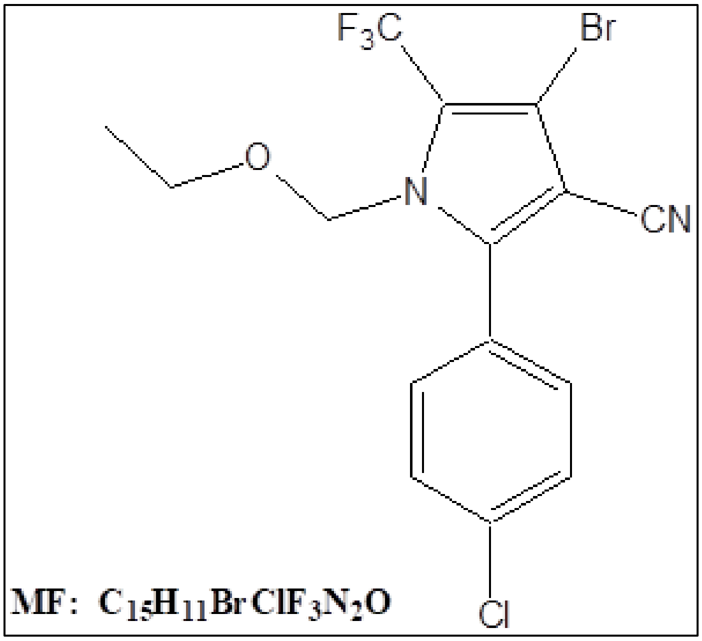
Chemically, Chlorfenapyr is a member of the class of pyrroles that is 4-bromo-1H-pyrrole-3-carbonitrile (cyano) which is substituted at positions 1, 2 and 5 by ethoxymethyl, p-chlorophenyl and trifluoromethyl groups, respectively whose structure is given in *Figure 5*.

Figure 5: Molecular structure of Chlorfenapyr



Recent reports however indicate that there is reduced susceptibility to chlorfenapyr in malaria vector *Anopheles gambiae*, contrasting with full susceptibility in *Anopheles funestus* in Africa (Tchouakui et al., 2023).

TREATED BEDNETS' EFFECTIVENESS AND DEPLOYMENT

Bednet treatments are better on LLINS because the insecticide as well as insecticidal effects are more evenly distributed. LLINS have additional advantages such as reduced insecticidal consumption and minimum potential environmental impact (Guillet et al, 2001). A candidate net will be deemed to meet the requirements for an LLIN if, at the end of three years use, at least 80% of the sampled nets retain bio-efficacy (i.e., ≥95% mosquito knockdown rate or ≥80% mortality) with a standard WHO cone bioassay or with a tunnel test (≥80% mortality or ≥90% blood feeding inhibition) (WHO, 2005). To date, WHO Pesticide Evaluation Scheme (WHOPES) has listed 23 LLIN different prequalified LLINs products from 13 different manufacturers, including new LLIN technologies against pyrethroid resistant mosquitoes (UNICEF, 2022). Long-lasting insecticidal nets (LLINs) particularly, have contributed immensely to the reduction of malaria morbidity and mortality in children below five years (Diouf et al., 2022). The world malaria report 2021 attributed the global prevention of 241 million malaria cases, 667,000 deaths and reduction in incidence from 80 to 57 worldwide majorly to treated nets (WHO, 2021). The interpretation of research findings that replacing bednets before useful lifespan is better for malaria control (Ngonghala, 2022) heralds a near future of their continued and increased manufacture, if funding allows. Further, field research indications that serviceable lifespan of LLINS could be less than two years (Gnanguenon et al, 2014) only means more frequent bednet replacement. In fact, model predictions in Tanzania recently advocated for annual distributions of treated nets rather than mass distributions every three years owing to the LLIN retention time to about two years (Koenker et

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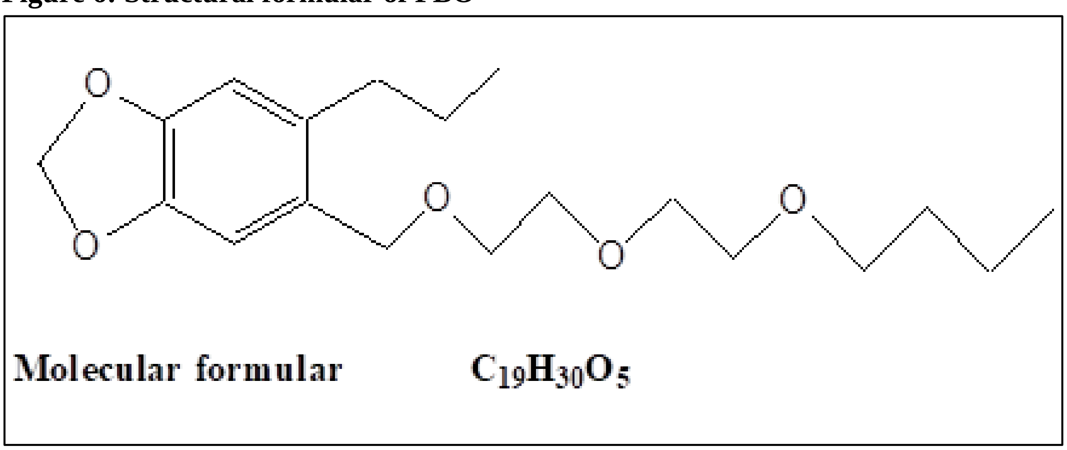
al., 2022). Considering the UNICEF procurement estimate of 28 million and 32 million nets in 2022 and 2023 respectively, with estimates of current LLIN production capacity being 480 million nets annually and an annual increase of 16% (UNICEF, 2022), a large number of treated bednets is expected in the environment.

As a result of LLINS recognized role in war against malaria, strategic mobilization of resources for their procurement and enhancement of their distribution and coverage has tremendously increased their supply for use (WHO, 2015; Aïkpon et al., 2020; Worrall et al, 2020). 253 million and 229 million treated nets were delivered by manufacturers to malaria endemic countries in 2019 and 2020 respectively, 91% of which channelled to sub-Saharan Africa (WHO, 2021). The percentage of households owning at least one LLIN for every two people increased from 1% in 2000 to 34% in 2020 (WHO, 2021). Similar data for the period of 2004–2020 show that almost 2.3 billion treated nets were supplied globally, of which 2 billion (86%) were supplied to sub-Saharan Africa (WHO, 2021). Long-lasting insecticidal net (LLIN) procurement amounts vary from year-to-year in accordance with country requirements but in general, countries procure new and replacement LLINs for distribution in mass campaigns on a two- to three-year cycle (UNICEF, 2020). After WHO recommendation that LLINs be provided free, Multilateral, and bilateral donors and programs such as the Global Fund against HIV/AIDs, Tuberculosis, and Malaria and the President's Malaria Initiative now support the purchase of LLINs for many countries through various channels of individual donations (CDC, 2019).

The effectiveness of treated bed nets has recently been challenged by widespread evolution of insecticide resistance in key vectors (Munywoki et al 2021; Osoro et. al, 2021; Sanou et al, 2021). Globally, resistance to pyrethroids – the primary insecticide class currently used in ITNs – is widespread, being detected in at least one malaria vector in 68% of the sites (WHO 2021). This development has prompted modification of bednets in many ways including use of dual active ingredients such as the synergist piperonyl butoxide (PBO) and pyrethroids. PBO (see structure in *Figure* 6.) enhances the killing effect in mosquito populations that exhibit metabolic resistance. Since 2010, PBO has been observed to fully restore susceptibility in 283 sites across 29 countries (WHO 2021). If this susceptibility trend is sustained, production and distribution of treated nets are bound to be escalated in this era of malaria elimination. Insect growth regulator pyriproxyfen is also used in conjunction with insecticides. Since treated bednets being manufactured currently are LLINs, the words ITNs, bednets and LLINs will now be used interchangeably for the rest of the article.

Figure 6: Structural formular of PBO



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Treated Bednets and Environmental Pollution

Wastes, if not well managed can pose a threat to the environment thereby endangering life. The general waste management prescription of 3Rs of reducing waste generated, reusing old items for other purposes and recycling does not fully apply to treated bednets. Reduction for example is not conceivable due to the recognized role of ITNs as invaluable life savers in especially malaria endemic areas. Although recycling still plays a role in solving the plastic menace, it may be plagued with challenges often faced by other plastics including safely of workers involved, expensive or inadequate services and low market demand for recycled materials (Huun, 2022). Furthermore, facilities for bednet recycling have not yet received enough support and therefore the option largely remains an unavailable solution to date (Brake et al., 2022). Reuse (also referred to as repurposing in the paper) is feasible but eventually requires proper disposal.

Since bednets are synthetic polymers, they contribute to environmental plastic pollution if they are not properly disposed-off, when they are misused and when washing recommendations are not followed. In one LLIN, there is approximately 500 g of plastic in addition to up to 30-80% of the full beginning-of-life dose of pesticide that remain in nets up to 7 years old (Ramanantsoa et al., 2017). Although initially dismissed based on anecdotal account (Eisele, Thwing & Keating, 2011), there is increasing evidence of misuse of ITNs for many purposes including use of nets for fishing, drying fish, bed covering and cattle tying among others (Ramanantsoa et al., 2017; Larsen et al., 2018; Mutalemwa et al., 2018). It cannot be assumed that only unusable bednets are discarded or misused. They are sometimes discarded before their expected lifespan of three years due to many reasons but mainly when their physical integrity is compromised. In Tanzania, about 84% of LLINS were discarded before the next distribution campaign, normally after 3-5 years (Maduma et al., 2022). This should not be the case because available literature show that they are still protective even when they have holes (Maduma et al, 2022). However, there is a need to further document alternative bednet uses and to elucidate the extent to which new and expired nets are being put to secondary use (Ramanantsoa et al., 2017).

Besides being plastics, bednets contain pesticides. Of course, some pesticides are degraded in the environment. One of the ways by which they are depleted from the environment is photodegradation. Many studies use first-order kinetics to model the dissipation of pesticides in the environment because a half-life for the chemical can be defined. The half-life represents the calculated time for loss of the first 50% of the substance. However, in many cases, the time required for the loss of the remaining substance may be substantially longer, and the rate of disappearance may decline further as time progresses. This is often the case for the disappearance of pesticides in soil. Pyrethroids are usually degraded by sunlight and soil within 24 to 48 h of exposure (more than that of natural pyrethrins half-life of 11.8-12.9h), but in some cases, they can last for many days. (Elroby & Aziz, 2011; Luo & Zhang, 2011; Meyer et al., 2013) The biodegradation of the pyrethroid pesticide esfenvalerate by a bacterial consortium is similar to photodegradation process with related products (dos Anjos et al., 2020) Nonetheless, there is always a chance that synthetic pyrethroids affects a helpful microbial community and reduces soil fertility besides other negative effects.

Piperonyl butoxide (PBO) is a synergist used to prolong the effects of synthetic insecticides and therefore enhance efficacy against pyrethroid-resistant malaria vectors, is a pale yellow to light brown liquid organic compound. Piperonyl Butoxide, (5-[2-(2-butoxyethoxy) ethoxymethyl]-6-propyl-1,3-benzodioxole 2-(2-butoxyethoxy) ethyl 6-propylpiperonyl ether), is a toxic substance that causes a range of short- and long-term health effects (US Dept. of Health & Human Services, 2003) PBO is composed aromatic ring and ether

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linkages that are stable to the environment. It persists in air, water, and soil systems, thus affecting the other organisms.

World Health Organization recommends that worn out treated bednets should be collected and incinerated at high temperature or buried away from water sources preferably in non-permeable soil but should not be thrown in water bodies burned in the open (WHO, 2014). These recommendations are however flouted and therefore LLINS are burned in the open air thus releasing dioxins which are toxic to humans. Similarly, burying around or washing in water sources contaminates these sources and consequently endangers aquatic life. Studies conducted in Kenya and Tanzania indicated that bednets were washed in open water, repurposed for many uses, and thereafter trashed carelessly or burned (Mutalemwa et a., 2018; Kibe et al., 2019). Washing and burying near water sources release some insecticides in water and yet there is increasing evidence that deltamethrin has some level of toxicity. It has genotoxic and oxidative stress-inducing effects in the erythrocytes of a freshwater fish species (Ansari et al., 2009; Yang, Lim, & Song, 2020). A wide array of biomarkers has been employed to delineate the toxic responses of freshwater fish to various type II synthetic pyrethroids to which deltamethrin belong (Nasuti et al., 2003). Lu et al., (2018) gives a summary of deltamethrin toxicity mechanism in light of oxidative stress.

Pollution caused by bednet insecticides may also pose some health risks that arise from exposure during storage and transport, exposure to vapours, and dermal or oral contact (Anyanwu et al., 2004). For in instance, the metabolites from the type II pyrethroids contain the cyano groups (cyanotoxins) that are neurotoxic and can pose adverse health effects to animals and humans (Drobac et al., 2013). Though generally considered safe, current bednet impregnating chemicals' acute and chronic long-term effects should be further evaluated to allay the potential fears of neurotoxicity and neurobehavioral effects, and cancer risks. Limited literature from low- and middle-class countries shows inconclusive associations between prenatal pesticide (including pyrethroids) exposure, child growth, and birth outcomes (Bliznashka, Roy & Jaaks, 2022).

Recommendations

To address both the rate and the amount of pollution arising from insecticide treated nets, bednets' physical and chemical integrity, and search for new and safer insecticides must form the next research frontier. Bednets that last longer reduce the rate of their disposal. Several nanoformulations such as biologically synthesized nanoparticles through plant extracts, nanoemulsions prepared using the essential oils like neem oil and citronella oil and nanoemulsion of conventional pesticides like pyrethroids, serve as a promising nanopesticide and are eco-friendly with a better target specificity (Mishra et al., 2018; Baz et al., 2021). On the other hand, instead of using plastic polymers as materials for bednets, natural biopolymers should be well-thought-out. Cellulose for example offer an alternative and will contribute to sustainability efforts as well as the overall performance of the nets (Brake et al., 2022; Xu et al., 2021). Cellulose is abundant, renewable, and biodegradable. An impetus in this direction is that interactions of cellulose and active components have been studied for the development of slow-release systems such as fertilizers (Ye et al., 2019), environmental monitoring involving pesticides (Rana et al., 2021) and in repellent fabrics (Elsayed et al., 2021; Sun et al., 2020). If natural materials and pesticides are not possible in the short-run, sturdier bednets that last long should be designed (Santos & Curtis, 2021).

Probably the immediate available option lies within the framework of community sensitization on various aspects including proper disposal of used old bednets according to WHO guidelines, their repair or gifting for continued use (Mishra et al., 2018, repurposing as mosquito barriers in windows and eaves (Mishra et al., 2018, and screening small crops and poultry against insect pests (Mutalemwa

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et a., 2018; Maduma et al, 2022). Nevertheless, disposal information should also be indicated on the packaging of the bednets.

Economic and social cultural factors that underlie misuse should be understood and addressed. Use of nets for fishing or selling in Malawi has been associated with food insecurity and poverty (Berthe et al., 2019). A cost sharing scheme together with free distribution to the poor rather complete free distribution based on the number of households has been shown to improve bednet proper use (Doda et al., 2018). There should also be an arrangement that involves the local authority and the community to collect bednets at the end of their useful life either for primary or repurposed function. Finally, potential health impact of residual insecticides needs to be understood by the community in greater depth to dissuade potentially harmful practices. (Ramanantsoa et al., 2017).

In conclusion, treated bednets play a crucial role in prevention of malaria and other insect transmitted diseases. Their current physical and chemical design renders them candidates of environmental pollution with eventual deleterious effects to human health if they are either misused or not disposed-off correctly according to the recommendations of the World Health Organization. ITN misuse and improper disposal are functions of many socio-economic and cultural factors which require attention by the National control programs if maximum benefit from bednet protection and less environmental pollution are expected outcomes. Better still, new natural and biodegradable bioproduct replacements for the currently used polymer materials and insecticides offer a lasting solution to bednet environmental pollution.

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