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Loss of soil biodiversity through judicious use of synthetic pesticides, A case study of trans-Nzoia County Kenya-review

Wakhungu, N. Cynthia

Department of Applied and Technical Biology, Technical University of Kenya, P.O. Box 52428, 00200, Nairobi, Kenya.

Email: Cynthia.wakhungu@tukenya.ac.ke

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Abstract
Trans Nzoia County is one of Kenya's leading food basket regions and enjoys favorable climatic conditions for crop production. With climatic change, farmers face challenges of soil infertility and pest and disease infestation, contributing to crop yield losses. Trans Nzoia County farmers rely heavily on synthetic pesticides to boost crop production and yields. In Kenya, 44% of the chemical pesticides used are banned in the EU market. Of these, 76% of the total volume sold contains active ingredients such as glyphosate, mancozeb, and paraquat, categorized as highly hazardous pesticides. Pesticide-intensive agriculture is on the rise in Trans Nzoia County, and the associated pollution are the driving factor in the precipitous decline of soil biodiversity, such as ground-nesting bees and beetles. Also, overreliance on synthetic pesticides contributes to the loss of beneficial soil microorganisms such as mycorrhizal species and earthworms responsible for nitrogen fixation, organic matter decomposition, and water and nutrient absorption. The author provides insights into the extent of the loss of beneficial soil organisms through synthetic pesticides. This review discusses the impacts and costs of pesticide use on soil organisms and policy responses.
Keywords: Biodiversity, ecosystems, pesticides, soil organisms.

Introduction
Pesticides are synthetic or natural chemicals used in agriculture to manage pests, weeds, and plant diseases. Pesticides range widely from insecticides, fungicides, herbicides, nematicides, rodenticides, bactericides, etc. (Bernardes et al., 2015). In agricultural development, pesticides

are relevant tools for promoting plant protection to enhance crop yields. Pest infestation is responsible for approximately 45% of annual food production loss, and thus, it is necessary to adopt effective pest management practices, including pesticide application (FAO, 2014). Responsible application of pesticides aids in protecting crops from invasive plants or weeds, insects, and diseases. The past decade has experienced extensive growth in the global economy, especially in the agricultural and industrial sectors, leading to a surge in demand for agriculture-based chemicals, which harm ecosystems. Devastating future repercussions tend to accompany the judicious use of pesticides, thus posing havoc to human beings and other beneficial organisms due to their high toxicity and bioaccumulation properties (Bourguet and Guillemaud, 2016). Pesticides interfere with the reproductive abilities of living organisms and impair the endocrine system (FAO, 2019). Deleterious effects on the environment are associated with active ingredients such as dieldrin, endrin, mirex, chlordane, dichlorodiphenyltrichloroethane (DDT), and hexachlorobenzene (Yadav et al., 2015).

The global use of pesticides requires constant monitoring to ensure regulatory measures are put in place in situations where abuse is documented. The availability of such statistics aids in monitoring sustainable agriculture by assessing the global trade in pesticides and any limitations associated with access to the worldwide market. Alternative crop loss due to pest infestation can be achieved using biopesticides and developing pest-resistant crop varieties through genetic breeding (Alons, 2017). However, pesticide chemical application remains the preferred method to protect crops from yield loss compared to all other alternatives. Globally, total pesticide use (active ingredients) stands at 2.7 million tons, with 1.8kg/ha of worldwide application per cropland area compared to 1.2 kg/ha in the 1990s. Insecticides, herbicides, bactericides, and fungicides use has also increased from 41 to 52%. Regarding the formulated product trade, pesticides reached 7.2 Mt in 2020, valued at USD 41.1 billion (FAO, 2022a). With regards to demand, herbicides are the predominant pesticides (47.5%), followed closely by insecticides (29.5%), and fungicides account for 17.5%, with 5.5% being other pesticides (Fig. 1). This is an indication that the pesticide industry contributes immensely to the global economy.

Pesticides are widely used in the USA, China, Argentina, Italy, Brazil, Thailand, France, Canada, India, and Japan. Most African countries import pesticides from other continents, with most exported pesticides remaining within. As of 2020, Africa as a continent imported 850kt (USD 3.1 million) in the monetary value of pesticides 779kt (USD 2.8million) and with only 20kt being sold to non-Africa nations (USD 0.12 million). (Zhang, 2018).

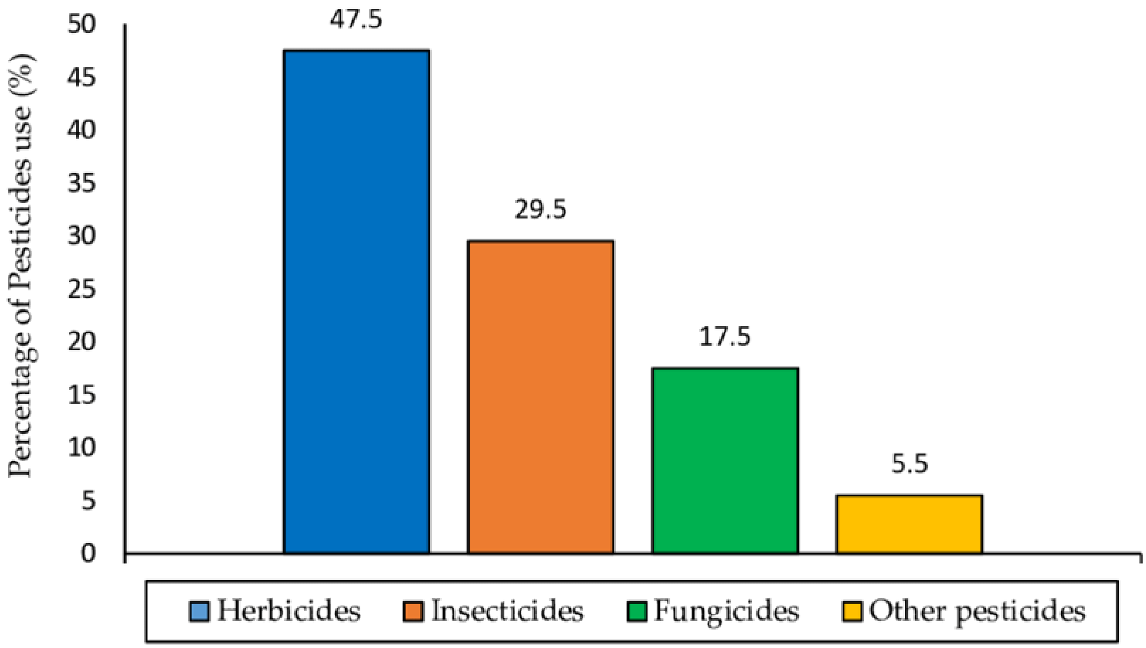

Figure 1. Global pesticide use (Sharma et al., 2019)

In agriculture, pesticides are primarily used to increase crop production; however, repeated use accumulates the pesticides in the water, soil, plant parts, and air. Persistent contamination of the environment by pesticides and retention in the soil enters the food chain, posing a significant threat to human beings and other terrestrial ecosystems. Depending on the chemical and physical properties of the pesticide used, prevailing environmental conditions, application procedure, and nature of the active substance, vapors are produced into the air (Mahmood et al., 2016). Pesticides also contaminate the air through the volatilization of water, and the dispersion gets them far and wide into the environment. Through surface runoffs, the synthetic pesticides get absorbed into the soil. Following the composition of organic compounds, irrigation techniques, climatic conditions, and cropping strategies, pesticide dissolution into the soil is often diverse and different (De et al., 2014). Groundwater gets polluted by pesticide residues through leaching into the soil, affecting the soil ecosystem's quality. Since soil is a storage compartment and considering its high affinity with organic chemicals, pesticides can accumulate in the soil directly through application and domestic uses or indirectly through airborne deposition. Soil organisms are directly exposed to chemicals from synthetic pesticides, increasing biodiversity loss and causing risks to other higher organisms, such as humans, through dietary intakes (Mahmood et al., 2016).

Following the evidence that synthetic chemicals have severe and long-term effects on the environment and ecosystems, their judicious use by developing countries without strict adherence to safety measures is worrisome. The ban by the EU regarding the export of highly hazardous pesticides to Africa by firms headquartered within the bloc has not deterred the demand and use of these chemicals in agriculture. The effects of synthetic pesticides on humans and ecosystems contradict the United Nations' sustainable development goals and threaten global food security (Yadav et al., 2015). Globally 9 million deaths are associated with environmental pollution, and pesticides are among the significant environmental pollutants. The HPPs are either carcinogenic, mutagenic, or neurotoxic (Blakey et al., 2013). The deleterious impacts of pesticides on the ecosystems need urgent understanding and consideration during these times when repercussions of climate change are constraining the availability and access to food.

African countries account for a quarter of global pesticide uses, and hazardous pesticides still exist in the African market. CropLife International reported a sale of 15% of HHPs in Kenya in 2015. The rising demand for pesticides such as herbicides and insecticides can be attributed to disease outbreaks following climate changes and the changing opportunity costs for labor, where hiring local workers to weed farms is quite expensive.

Since Africa does not control active ingredient production, Kenya relies on imports from China (42%) and the EU (30%). Agriculture, which accounts for 30% GDP in Kenya, heavily depends on pesticide use. Between 2015-2019, pesticide importations in Kenya increased from 6400 tons to 15600 tons as per the Associations of Agrochemicals of Kenya (AAK, 2018). In Kenya, agricultural practices have intensified, and this is because of increased market integration, population growth, and urbanization; due to climate change, pest and diseases pressure on crops has also intensified with recent cases of epidemics such as maize lethal necrotic disease outbreak (2012), desert locusts and fall army menaces. Kenya also serves as a significant market for pesticides banned within the EU.

Trans Nzoia county sits on an area of 2 495km^2 and lies between latitudes 00° 52´ and 01° 18´ north of the equator and longitudes 34° 38´ and 35° 23´ east of the prime meridian (Jaetzold et al., 2010). Agriculture is the main income-generating activity in Trans Nzoia County, with most of the population participating in subsistence and commercial farming. The county enjoys favorable weather and has good arable land; thus, the residents practice crop production and animal rearing. Some crops planted include maize, beans, millet, sorghum, and Irish potato, accounting for 70% of the total crop produced (Lalah et al., 2022). Pesticide use for agricultural purposes in Trans Nzoia has increased in the past decade, and their side effects are already being experienced; these include loss of soil and terrestrial biodiversity and a surge in invasive plant species, most of which are parasitic (Onyando et al., 2023). Following extensive use of pesticides for agricultural practices globally and specifically in Trans Nzoia County, Kenya, the current review provides insight into the effects of pesticides on the soil ecosystems and the projected contribution to biodiversity loss amidst devastating climatic changes.

Material and methods

A preliminary literature search was done using CABI and google scholar sites for specific pesticide use in crop protection. The search aimed at determining the extent of research done on the impacts of pesticide use on the environment and natural ecosystems biodiversity around the globe as well as the economic/monetary value of the pesticides industry, which serves as a reflection of the product’s demand. The search was then narrowed down to the effects of pesticide use on soil biodiversity as a projection of the same effects on Kenya, specifically Trans Nzoia County. The used search terms included (pesticides OR insecticides OR fungicides, OR herbicides) AND (environmental pollution OR terrestrial OR soil, OR nontarget organisms) which were used to determine review articles and research papers for further resources. For a second round of literature search, more specific search terms were informed by the soil microorganisms included in the corresponding bibliographies combining (herbicides OR insecticides OR fungicides plus organophosphates and HHPs were also crucial search terms). For an exhaustive data search, diverse and multiple combinations of key search words were used in selected databases and journals (PubMed, Agricola, Nature, Directory of Open Access Journals, SpringerLink, Ecotoxicology and Environmental Safety, Environmental Pollution, European Journal of Soil Biology, PLos, Science Direct, Frontiers. A brief scan of the title and abstract of each paper was done for relevance, and 695 studies were identified. Following further review of the papers, the articles were reduced to 41. (See reference section). Most of the excluded materials did not meet the inclusion criteria, could not be accessed, and others were not in English.

Criteria and relevance

The following criteria guided all papers included in this review: 1 The target pesticides must be chemical and not biopesticides. 2 The study must have a biodiversity aspect and the impact synthetic pesticides have on ecosystems 3. For soil biodiversity, the study must include non-target soil organisms. 4 The toxic effects of the pesticides must be reflected in the study. The studies focusing on pesticide behavior were also mentioned in the review, including volatilization, runoff, persistence, leaching, and dissipation. These soil interactions are necessary for determining the prolonged effects of pesticides on the soil ecosystem. The efficacy of ecotoxicity testing methods was not included in this work as its beyond the scope of the review but necessary for future reviews.

Global use of pesticides

Pesticides have been used in agriculture for crop protection since the early developments, with elemental sulfur being the first known pesticide dating back to 4500 years in Mesopotamia (Sharma et al., 2019). Substances such as tobacco extracts, brine, vinegar, and oil soap dominated the pesticide industry in the 17th and 18th centuries, with copper sulfate, lime, and water used to manage downy mildew on grape vines. Inorganic chemicals like arsenic, sulfur, copper, and plant extracts from pyrethrum and rotenone became famous in the 20th century. They were used mainly as fungicides and insecticides (Zhang, 2018). In the early 1940s, farmers mainly relied on agronomic practices such as intercropping, crop rotation, and field hygiene to manage crop pests. It was in the late 1940s that organic chemicals were introduced as herbicides, insecticides, and fungicides. Some of the standard classes of insecticides include neonicotinoids, pyrroles, and spinosyns. Fungicides include carboxamides and strobilurins, while herbicides include pyrimidinediones, triazolones, and benzoyl pyrazoles (Boone et al., 2014). Over 600 active chemical ingredients are on the market compared to about 100 in the 1960s (Zhang, 2018). Following stricter human health and environmental requirements by large economies such as the EU market, pest companies have become increasingly difficult to introduce new active ingredients. Combined with excellent biological efficacy, such a move saw a drop in the application rates, averaging between 1000-2500 g/ha in the 1950s and 40-100 g/ha in the 2000s.In 1991, introducing the EU-wide plant-protection registration system led to more than half the 1,000 active ingredients not being re-introduced into the market (FAO, 2018). However, these banned products have been dumped in developing countries, negatively impacting human and environmental health.

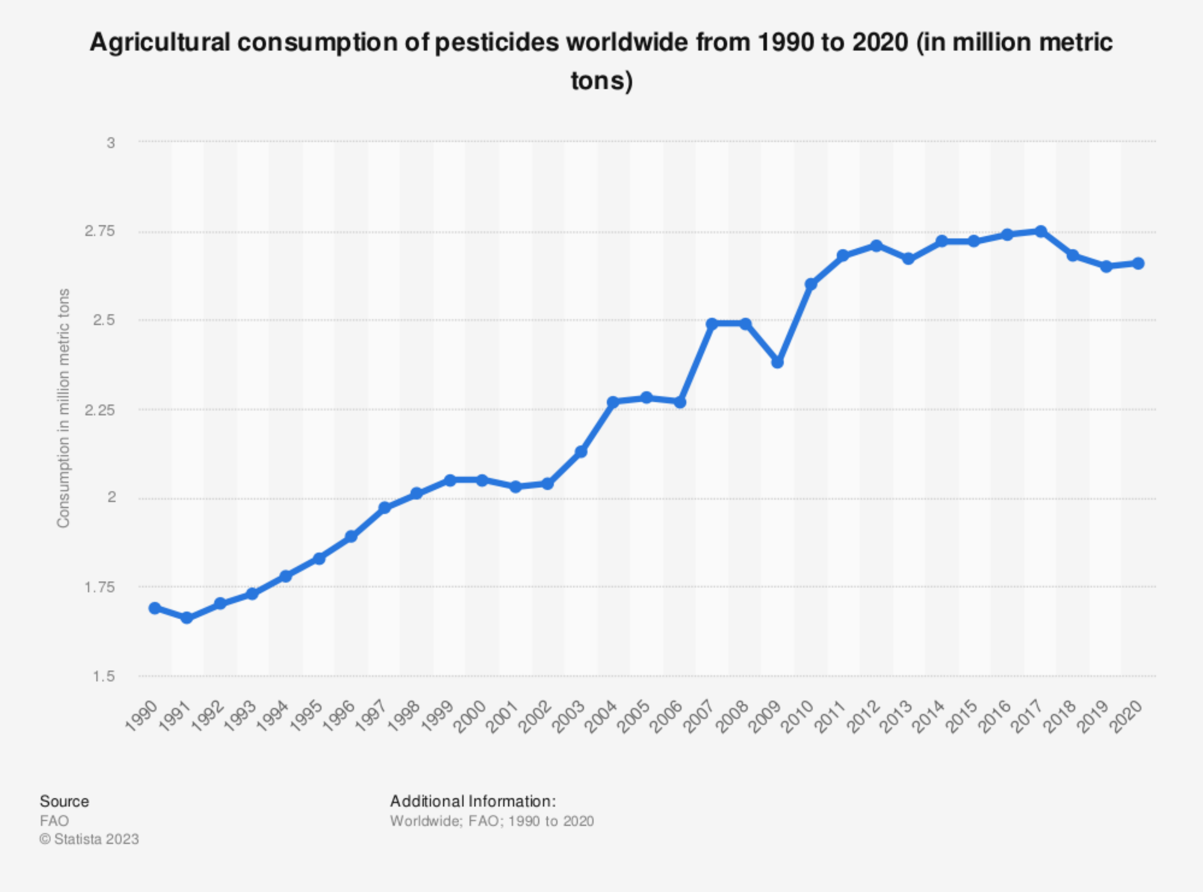

Figure 2. Global pesticides consumption: live link- http://www.fao.org/faostat/en/#data/RP/visualize

Since the introduction of synthetic pesticides in the 1940s, their global use has constantly been increasing, and in recent years their use has hit a mark of over 6.7 million tons of active ingredient (Fig. 2). South, the Caribbean, and Central America record the greatest pesticide growth, with Asia using more pesticides than all the continents combined. The Oceania region has the lowest pesticide use, but the same region has registered the second highest growth rate. The strict measures regarding pesticide use and manufacturing in northern America have led to a slight increase of 10%, while Europe has seen a decrease in use (De et al., 2014). Pesticide uses are 25-40% higher compared to the manufacturing rates. Per capita, gross domestic product (GDP) varies across regions hence differences in pesticide use. For instance, between 1991 and 1995, most pesticides were used by low- and high-income countries, while in 2012-2016, most pesticides were used by upper-middle-income countries (FAO/WHO, 2016). Upper middle-income countries such as China are responsible for significant shares in global pesticide use linked to intensive and large-scale agricultural practices. The use of pesticides in low-income countries does not exceed 7% of total global pesticide use. However, these countries face relatively increased pesticide use annually (Midingoyi, 2019). In 2020, Europe recorded the most minor pesticide use per cropland area (1.6 kg/ha). In the same year, the highest imports of pesticides were made by Americans at a dollar valued at USD 6.9 billion. The region has thus used the highest number of pesticides per cropland area, i.e., 2.83 kg/ha/year. Africa uses a minor level of pesticides, i.e., 0.11 tons per year, and applies the least per cropland area (FAO, 2022). Most regulators are concerned with health hazards associated with pesticide use, disregarding their effects on non-target organisms, especially in Africa. The persistence of pesticides in the environment for many years poses worldwide threats to the ecosystems on which food production depends. Loss of biodiversity is the significant direct effect of excessive pesticide use that contaminates soil and water. Destruction of beneficial insect populations like bees and termites has been noted by communities living near commercial agriculture farms (EFSA, 2017).

Pesticides use in Kenya

About 24% of Kenya's GDP is accounted for by agriculture, with close to 70% of those living in rural setups working in the sector (Onyando et al., 2023). Kenya hugely depends on conventional agriculture, and thus the demand for chemical pesticides is very high, especially in the highlands (Fig. 3). For instance, pesticides worth 17 803 tons valued at 128 million USD were imported by Kenya in 2018. Of the import's fungicides, herbicides and insecticides account for 87% volume-wise and 88% total cost. Volumes of imported insecticides also doubled from 6400 tons in 2015 to 15 600 tons in 2018, reflecting a 144% growth rate (Lalah et al., 2018). There is, therefore, the need for necessary safeguards and measures to control pesticide application and use in Kenya. Insufficient data exist regarding pesticide concentrations in water, soils, and food, as well as related impacts, with most research focusing on persistent organic pollutants like DDT and endosulfan. Heavy use of pesticides has made them widely abundant in the environment, leading to decreased water and soil quality and increasing damage to ecosystems. In most cases, a mixture of pesticides is present in the environment, and the total accumulative effects of the mixtures on biodiversity are still unknown (Loha et al., 2018). The hazardous pesticides are either acutely toxic, may be endocrine disruptors, or toxic to wildlife species and can cause severe irreversible adverse effects.

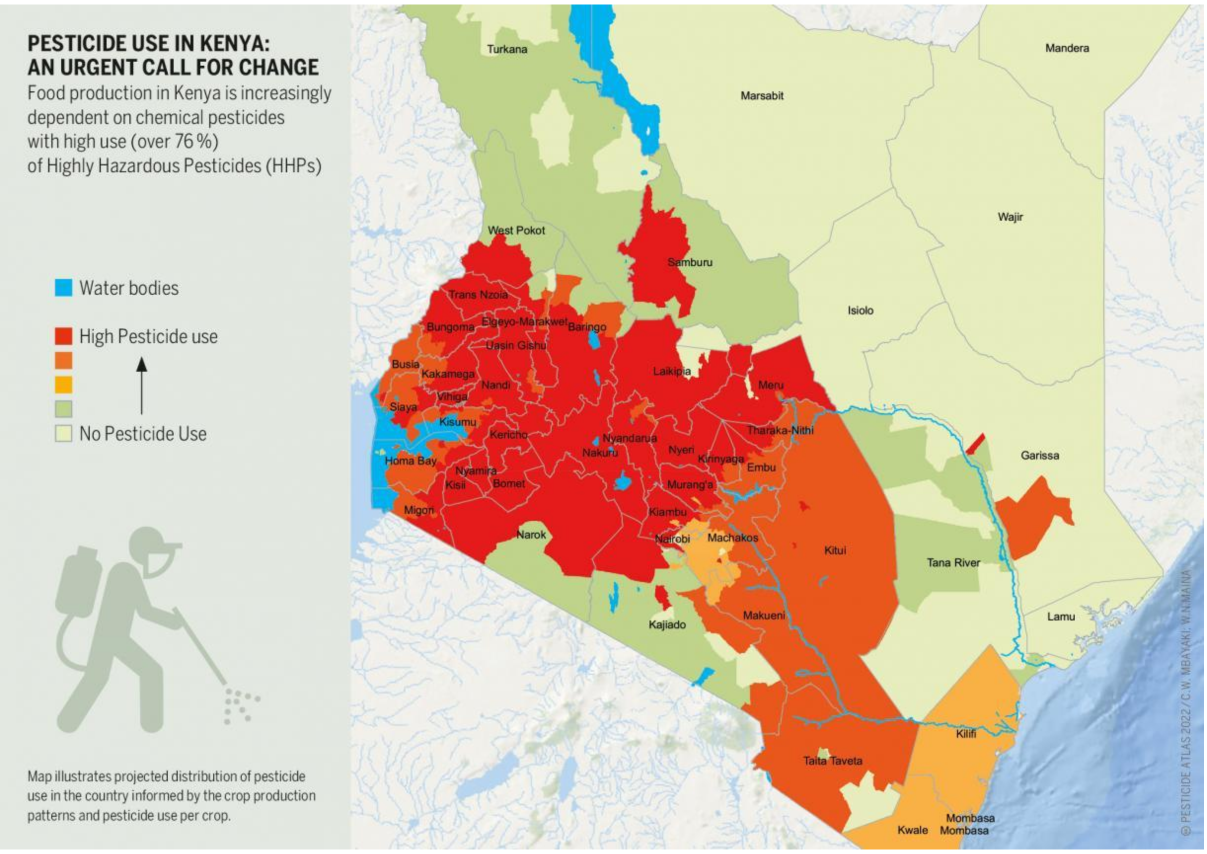

Figure 3. projected distribution of pesticide uses in Kenya.
https://ke.boell.org/en/2022/10/31/pesticide-use-kenya-toxic-business

Pesticides use and regulation in Kenya is a mandate of the pest control and products board (PCPB), formed in 1982 by the pest control products act. Kenya has close to 1700 registered pesticide products, where 83% are used in the crops industry; 9% in public health; 6% fall under technical grades for local formulations; and only 2 percent are under temporal restriction (Odino and Ogada 2021). According to PCPB, 862 horticultural products have 230 active ingredients, excluding active ingredients for flower and forest management and biological controls implying that the number could be higher. In Kenya, nearly 45 products are termed carcinogenic, 31 mutagenic, 51 endocrine disruptors, 175 neurotoxic, and 360 affect the reproductive system (PCPB, 2018). Active ingredients such as carbendazim, acephate, chlorothalonil, and permethrin have been banned in the EU and Kenyan markets but are still sold in Kenya. Mancozeb, found in nearly 78 products, was confirmed to affect the reproductive systems of living organisms negatively. Studies by the national pesticide residue monitoring program (NPRMP) revealed pesticide detection in 530(47%) of the 1139 samples collected in the fields. At the same time, 123(10%) exceeded the maximum set residue levels by the EU. Some predominant active ingredients were profenofos, imidacloprid, cypermethrin, and azoxystrobin. Kales, capsicum, and peas recorded the most pesticide residues (Omwenga et al., 2021). These statistics indicate that farmers, users, and operators are directly exposed to hazardous pesticides, with soil organisms facing huge impacts but less acknowledged. Measures to reduce risk and public health problems need to factor in the variation in toxicity of different pesticides for humans and the environment.

Major pests affecting crops in Kenya's subsistence farming are insects, fungal diseases, and weeds. Hence the high demand for insecticides as compared to other forms of pesticides (Fig.4). Most common pests are caterpillar-related ones (84%), and these are worms, white flies, stalk borers, cutworms, armyworms, weevils, termites, fungi and rodents (Lalah et al., 2022). It, however, is essential to acknowledge that despite these insect pests being detrimental to crops, they play a massive role in ecosystem sustainability, and there is a need for nature-friendly solutions to be used in controlling the pests. However, in most cases, synthetic pesticides act to eliminate and not control the population of these pests, leading to potential extinction.

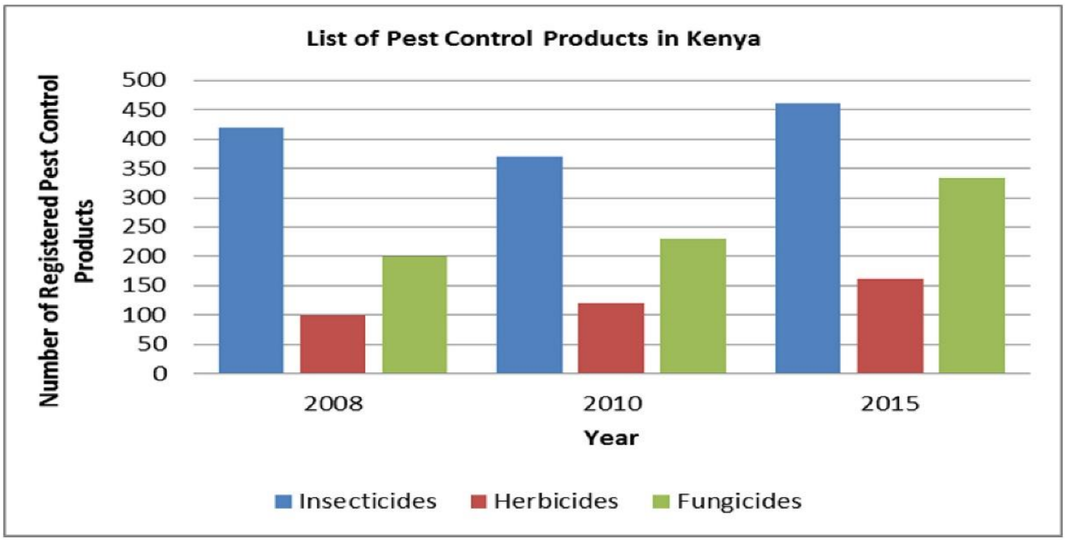

Fig 4. Pesticides use and registration in Kenya (Loha et al. 2018)

Extensive use of pesticides in Kenya has been reported in areas that are traditionally agricultural zones, Trans Nzoia County included (Fig.3). Since the year 2000, many cases of pesticides misuse and occupational exposure leading to human health risks have been documented in these regions (Macharia, 2015). The risks associated with pesticide use are dire in Kenya compared to developed countries due to the lack of necessary precautions. Pesticide registration in developed continents such as Europe is done with strict measures compared to Kenya, thus leading to higher exposure risks to farmers, the environment, and consumers. For instance, more Kenyans (70%) work in the agricultural sector due to high mechanization compared to 5% in Europe. Most farmers and laborers do not use PPE as required when handling highly hazardous pesticides. The application equipment like knapsack sprayers is less sophisticated and often not in good condition, i.e., leakages, etc., compared to Europe. Distances, poverty, ineffective extension systems, limited education, etc., limit the feasibility of reaching all farmers with necessary training. Most farming systems are along water bodies and hill slopes, and thus risks of runoffs are high, and the small farm sizes make it hard to implement mitigation measures such as buffer zones. In Kenya, most farm workers who directly handle the pesticides are illiterate or semi-literate and thus unable or do not find it necessary to read the labels before use. Thus, farmers also have limited knowledge about pesticide use and associated risks (Otieno et al., 2014).

Some crops heavily relying on pesticides include maize, beans, and horticultural products. Trans Nzoia County is the largest maize producer in Kenya, producing 5 million bags annually from approximately 107 000 acres of cultivated land (Oyaro et al., 2022). In Trans Nzoia County, 25 active ingredients are significant in the environmental and human health impacts. The most commonly used active ingredients include metalaxyl-M, mancozeb, glyphosate, terbuthylazine, and carbendazim. Diazinon is not heavily used in Trans Nzoia but also significantly impacts the environment. Of all the active ingredients used, 19% combine metalaxyl-M and mancozeb. This is because the county is damp and cold most of the year, and these conditions favor fungal disease infestation. Due to large farm sizes (5-100 acres), there is heavy reliance on herbicides by farmers in Trans Nzoia County, and these include glyphosate, paraquat, atrazine, and metolachlor (Table 1).

The active ingredients have a high potential of contaminating surface and ground waters in the region. According to weighted hazard potential, glyphosate, mancozeb, and topramezone+dicamba present significant risks, but due to their low GUS index, their potential of contaminating surface and groundwater is low (Onyando et al., 2023). Of great concern to the ecosystem and biodiversity effects is thiamethoxam, which has a high GUS index and high SWMI score and is also reported to be highly toxic to the environment, birds, aquatic invertebrates, mammals, and bees (Otieno et al., 2014). Oyaro, Nyamari, and Musau (2022); reported that most farmers in Trans Nzoia Kenya use a combination of pesticides (close to 10) on their farms in various formulations, most of which are HHPs. Such pesticides include carbendazim (32.9%), metolachlor (28.2%), amitraz (56.3^%), diazinon (20.4%), epoxiconazole (17.6%), imidacloprid (23.6%), chlorpyrifos (10.6%), and acetochlor (9.1%). The most used class of pesticides is organophosphates (34.8%), of which 18.4% are persistent in the soil, and 31.6% in the water, with 13.2% and 10.5% being key contaminants of surface and groundwater. Regarding bioconcentration in living tissues, 18.4% of the synthetic pesticides, including amitraz, heptachlor, lufenuron, and copper oxychloride, are common in Trans Nzoia County. 18.8% and 39.5% of the chemicals are hazardous to earthworms and aquatic invertebrates (GoK, 2018, 1-13). Soil and aquatic ecosystems contribute to the highest percentages of biodiversity. Thus, such figures threaten biodiversity loss affecting the region's agricultural sustainability and food security. Compared to global expectations, little research on pesticides and their impacts is being conducted in Kenya. However, in recent years, pesticide use policies in Kenya are becoming impactful; for instance, the Route for food initiative (RTF, 2021) established that of the 230 registered ingredients in Kenya, 77% had been withdrawn from the agro vets following their detrimental effects.

Table 1. Pesticides used in Trans Nzoia County: The Intrinsic Toxicity Potential (ITP), Hazard Potential (HP), Weighted Hazard Potential (WHP), and Mobility. (Lalah et al., 2022)

Pesticide	**Quantity Kg(a.i)**	**%Use**	**ITP**	**HP**	**WHP**	**Mobility**
Metalaxyl+ mancozeb	6678	19.6	3	6	1.2	Low
Glyphosate	5140	15.1	21	21	3.2	Low
Mancozeb	4443	13.0	15	15	2.0	Low
Terbuthylazine	4125	12.1	11	14	1.7	Medium
s-metolachlor + Atrazine	3561	10.4	7	14	0.1	High
Paraquat dichloride	1774	5.2	10	10	0.5	Low
Tebuconazole	1244	3.6	11	22	0.8	Medium
Lambda-cyhalothrin	1230	3.6	5	5	0.2	Extremely low
Imidacloprid	846	2.5	6	6	0.2	High
Atrazine	507	1.7	7	14	0.2	High
Carbendazim	465	1.4	11	22	0.3	Medium
Hexazinone	436	1.3	3	6	0.1	High
Carbosulfan	376	1.1	1	1	0.01	Low
Abamectin	367	1.1	10	10	0.1	Low
Deltamethrin	362	1.1	20	20	0.2	Low
Topramezone + dicamba	354	1.0	10	40	0.4	High
s-metolachlor	354	1.0	15	30	0.3	Low

Alpha-cypermethrin	344	1.0	14	14	0.1	Extremely low
Cymoxanil + prominent	344	1.0	15	23	0.2	Low
Chlorpyrifos	278	0.8	9	9	0.1	Low
Thiamethoxam	223	0.7	3	4	0.03	High
Cyhalothrin	221	0.3	9	9	0.1	Extremely low
2,4-D-Amine	181	0.5	9	36	0.2	Medium
Profenofos + cypermethrin	167	0.5	15	40	0.1	Extremely low
Diazinon	122	0.4	15	23	0.1	Low

Effects of pesticides on ecosystems

From inception, agricultural pesticides were introduced to protect crops against pests and diseases and to promote crop yield; however, the associated risks from their use have surpassed the benefits with drastic and irreversible impacts on non-target species affecting plant and animal biodiversity, including terrestrial and aquatic food webs and ecosystems (Zhang, 2018). Most pesticides, such as herbicides, can volatilize during the spraying session and evaporate into the air causing harm to non-target organisms. Judicious and unsupervised use of pesticides has led to the loss of animal and plant species and threatened the survival of rare bird species such as osprey, bald eagle, and peregrine, contaminating water and soil bodies to toxic levels. The most toxic category is insecticides, fungicides, and herbicides (Bernardes et al., 2015). Pesticides contaminate natural ecosystems by dissolving in water or through bio amplification for the fat-soluble pesticides. The absorption of pesticides in the fatty tissues leads to persistence in food chains for extended periods. With bio amplification, the pesticide concentration increases as the trophic level rises, and the whole ecosystem is disrupted due to the loss of more species in the higher trophic levels to more significant toxicity (Mahmood et al., 2016). Hence the uncontrolled use of pesticides cannot be overlooked as the threats are severe to terrestrial inhabitants.

From an indirect perspective, pesticides reduce populations of insects, weeds, and shrubs, which are food sources for higher orders. For instance, regarding aquatic biodiversity, pesticides enter water bodies through runoff, drifts, and leaching in the soil. Pesticides affect aquatic lifestyle by destroying aquatic plants and decreasing dissolved oxygen, causing physiological and behavioral changes in aquatic populations such as fish. Pesticide levels are higher on the surface than on ground waters due to excessive surface runoff and spray drifts.

Among the toxic pesticides affecting aquatic ecosystems are atrazine, carbaryl, and glyphosate, which affects the immune system of fish and amphibians ((Singh Sankhla et al., 2018).

Terrestrial biodiversity is often tampered with by inappropriate use of pesticides. For instance, phenoxyl herbicides damage and kill non-target herbs and shrubs, while glyphosate increases plants' susceptibility to diseases through reduced seed quality. Approximately 40% of insect species are declining globally due to pesticide use in agriculture (Blakey et al., 2013). The decline in pollinator populations puts the multibillion-dollar agriculture sector at risk, attributed to heavy reliance on chemicals for farming. There has been a reduced population of beneficial bees and beetles through broad-spectrum insecticides like pyrethroids, organophosphates, and carbamates. For instance, honey bees are often susceptible to the synergistic effects of triazole and pyrethroids. Bee foraging behaviors are affected by clothianidin and imidacloprid (Desneux et al., 2007). At the onset of the 21st century, a sudden decrease in the population of honey bees was caused by neonicotinoids, and the trend has been persistent, with a loss of 29-36% in bee populations (Kuan et al., 2018). A decline in the population of bees is a threat to the food industry since crop production is heavily dependent on bee pollination. The massive decline in bird populations (20-25%) has also been recorded since pre-agricultural times, with the primary cause being the use of pesticides. The population of grouse, pheasants, and partridges, i.e., insect-eating birds, has drastically reduced due to the loss of insects to insecticides (Arya et al., 2019). Any loss of rare and endangered animal species often pushes them to extinction.

Indirect and direct loss in animal and bird species also results from fungicides. For example, carbofuran, an active component of carbamates, has been used in agricultural farms on Kenyan soil for many years, and the effects are as devastating as those of organophosphates. Carbofuran is traded as Furadan 5G and has decimated lion populations close to extermination. By the early 2000s, lion populations were estimated at 2000, down from 50000 in the 1950s. Vultures feeding on poisoned carcasses die in large numbers because nearly 100 vultures feed on one poisoned carcass; therefore, indirectly, carbofuran has contributed to a decline in the vultures population in Kenya. Baits have also been laced with carbofuran to poison whistling ducks (Dendrocygna spp) in rice plantations, while termite baits have been used to kill insect-eating Abdim's stork (Ciconia abdomen). (Odino and Ogada 2021)

Pesticides use and soil biodiversity loss

Soil as a microsystem harbors microorganisms that play essential roles in nutrient recycling, thus contributing to the maintenance of soil fertility and allowing sustainable agricultural productivity. Soil ecosystem contributes to 25% of ecological biodiversity with millions of beneficial microorganisms such as nitrogen-fixing bacteria, and the damage of these microorganisms leads to instability in the ecosystem, including aquatic and terrestrial spaces (Rose et al., 2016). Soil microorganisms aid in plant nutrient uptake, increase soil fertility, and break down organic matter. Different human activities centered on agriculture significantly contribute to the loss of soil biodiversity (Fig. 5). Pesticide use may contribute to the extinction of soil microorganisms leading to soil degradation. For instance, the nitrogen-fixing process is crucial in plants, and triclopyr dinitrophenyl and chlorothalonil have been found to interfere with nitrification and de-nitrification bacteria-dependent processes. Protists, fungi, and bacteria aid in metabolizing decaying matter converting it into organic waste and minerals like nitrates. Fungi such as white rot can degrade lignin, which potentially leads to the degradation of recalcitrant chlorinated pesticides like pentachlorophenol and toxaphene (Bender et al., 2016). Most pesticides are often applied as liquid sprays on plants or in the soil or as granules and seed treatment. They then disappear through dispersion, degradation, and volatilization or leaching into the surface and groundwater. The pesticides stay in the soil for long periods, and soil organisms may also take them up. Nonselective herbicides such as glyphosate reduce the activity and growth of nitrogen-fixing bacteria in soils with 2,4-D inhibiting ammonia transformation into nitrates (Bardgett and van der Putten, 2014). The growth of symbiotic mycorrhizal fungi is heavily hindered by the use of oryzalin and trifluralin fungicides, while fungal spores are reduced by oxadiazon. Mycorrhizal root colonization has been reported to reduce by 80% following the application of benomyl, thus indirectly affecting the abundance of predatory and fungal-feeding nematodes by 33%. Loss of mycorrhizal population also contributes to stunted growth and yield reduction. This is hugely significant when farmers use pesticides such as captan, carbofuran, and mercury-based fungicides. Reducing fungal populations in the soil by applying fungicides reduces litter decomposition by 25-36% (Riedo et al., 2021).

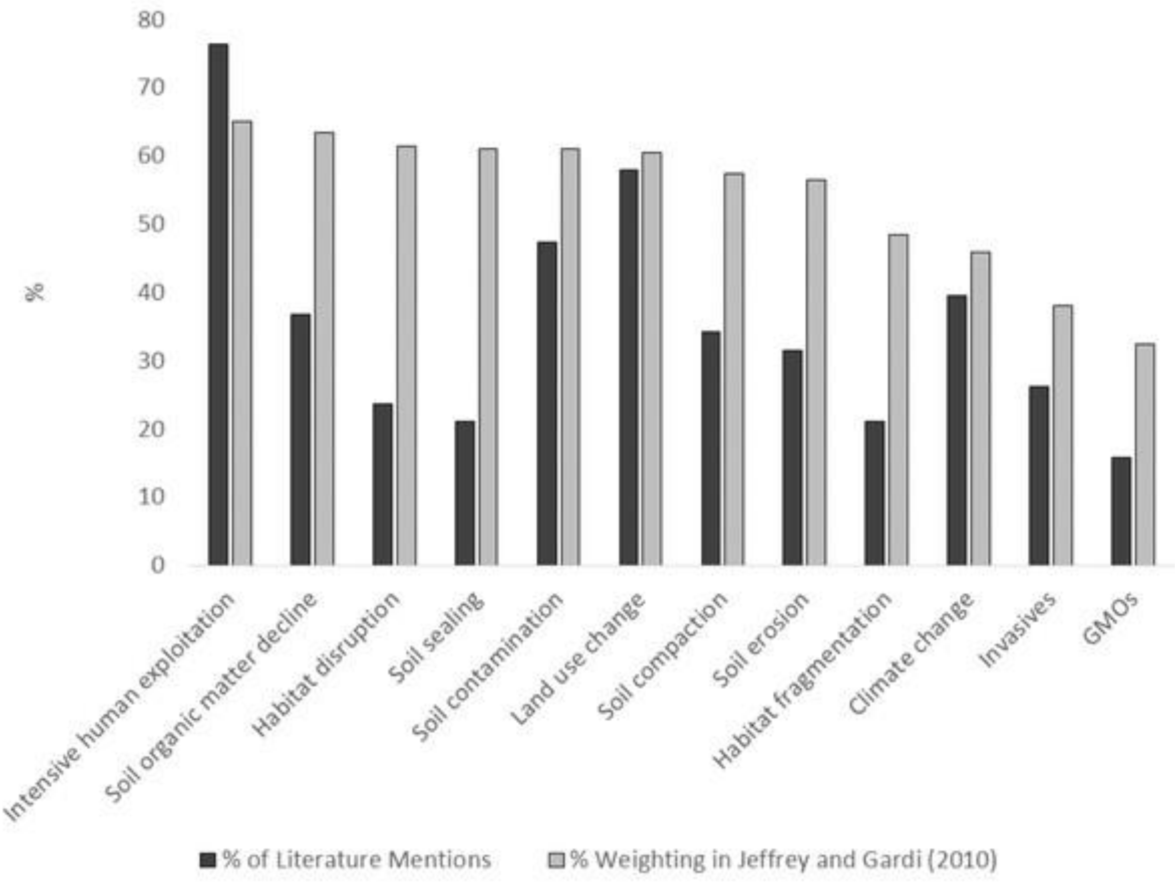

Fig 5. Soil biodiversity loss

A significant role is played by earthworms when assessing the soil profiles and fertilities as they serve as models of soil toxicity testing and indicators of soil contamination. Earthworms are also good contributors to soil fertility via the biodegradation of litter and other organic matter. However, earthworms are heavily exposed to pesticide toxicity through contaminated soil pores. Neurotoxic effects on earthworms are experienced through the use of insecticides and fungicides; following long-term pesticide exposures, the worms are physiologically damaged. At the cellular level DNA of earthworms is damaged by chlorpyrifos and glyphosates; they also affect the viability and feeding activity (Riedo et al., 2021).

Using fungicides such as captan and benomyl and herbicides like picloram and glyphosate reduces soil basal respiration by 30-50%. Soil community structure in agricultural fields is also significantly altered by applying metolachlor and atrazine to reduce methanotrophic bacteria. At the same time, maned and picloram hinder the mineralization of organic nitrogen to ammonium and nitrate in the soil by Nitrobacter and Nitrosomonas bacterial species. Despite the ability of glyphosate to hinder the biosynthesis of aromatic amino acids leading to the suppression of soil bacteria, it also contributes to the susceptibility of plants to pathogenic microorganisms by inhibiting the process of biosynthesis of glyceollin and phytoalexin that is responsible for blocking infections (Rose et al., 2016). In addition, soil mesofauna contributes approximately 11% to total carbon recycling for surface litter and 22% to buried litter in fields treated by pesticides. These minute animals can thus be decimated by insecticides, thus disrupting soil complex structure. However, populations of soil mesofauna recover quickly once the toxic activity disappears (Mahmood et al., 2016).

Not all plant materials can be disintegrated by soil microorganisms, and saprophytic arthropods such as Pauropoda, springtails, woodlice, millipedes, Diptera larvae, symphylids, and mites play such crucial roles. These roles are important in forest ecosystems; thus, the no-tillage agronomic practices draw benefits from such roles (Sánchez-Bayo, 2021). Pesticide residues in soils lead to a reduction in springtail species, i.e., Collembola, myriapods, saprophagous mites, and symphylids, and some of these pesticides include aldrin dieldrin, heptachlor, and DDT. Despite DDT being less toxic, it is reported to kill more predatory mites compared to dieldrin and aldrin (Desneux et al., 2007). For example, in Africa, the application of lindane has seen a reduction of up to 80% in springtail numbers contributing to reduced organic matter breakdown by 45%. Some populations of prosauropods are often eliminated by OP insecticides (Loha et al., 2018). Mites are the most abundant arthropods in the soil and are thus significantly impacted by pesticide use. They are either predators, saprophytic, or crop pests. The predatory mites are heavily affected by insecticides, with gamasina mites facing extinction. The use of D-D mixtures leads to the elimination of all mite populations. It does not allow recovery two years post-application, thus decreasing soil biodiversity (Konestabo et al., 2022).

Other soil predatory arthropods affected by pesticide use include earwigs, staphylinid beetles, spiders, and centipedes which DDT and Aldrin heavily destroy. Since sympylids live in deep soils, they can only be affected by soil leaching and hydrophilic pesticides. Most Diptera larvae are agricultural pests, but the majority still aid in decomposing organic matter, and thus repeated application of simazine causes loss in the larvae and accumulates organic material on surfaces. Dung beetles and flies in pasturelands are affected by the leaching of parasiticides in the feces of treated livestock (Sands and Wall, 2018). Therefore, judicious use of pesticides causes ecological disruption via a drastic reduction in parasites, pathogenic organisms, and predators controlling crop pests. Restoring the ecosystem’s natural balance is almost impossible, as the long-term effects of pesticides often hinder the re-establishment of the initial community structure.

Pesticides registration and legislation

Global Perspective

International treaties, codes, commissions, conventions, and advisory bodies guide pesticide management and plant protection aspects. Therefore, governments accept obligations that must be incorporated into national policies by ratifying international conventions. International governance on pesticides remains inadequate and weak, relying primarily on the international code of conduct on pesticide management set by WHO and FAO (2014). The code offers only guidelines and, thus, a more or less powerless mechanism on which actions need to be taken regarding reinforcing program implementation. A strategic approach for international chemical management (SAICM) was set up in 2006 but remains non-binding. The worldwide plan of action for SAICM, "promoting alternatives to reduce and phase out highly toxic pesticides'' has not developed any substantial actions and programs regarding their mandate. Most international conventions do not offer all round approaches to pesticide use. For instance, eliminating persistent organic pollutants was an assignment for the Stockholm Convention. However, only a handful of pesticides that are in use currently have been eligible for listing, and the process of adding others is long.

Some conventions only offer prior informed consent about hazardous pesticides but do not promote elimination from the market, and this includes the Rotterdam Convention on "prior informed consent procedure for some hazardous chemicals and pesticides" in international trade. This implies that deleterious pesticides can still be produced and made publicly available. FAO previously (2006) had proposed a ban on HHPs, but in 2016, the same body published guidelines to enable regulators to deal with highly hazardous pesticides (again, an aspect of leaving the decision to manufacture hazardous pesticides open). The guidelines set by FAO in 2006 aimed to ensure nationals end the use of hazardous chemicals, which was in agreement with the international labor organization's code of conduct on safety and health in Agriculture (FAO/WHO, 2023). The second regulation is a mitigation strategy that may not be adhered to by a majority of pesticide users once the hazardous products are in the market. However, the EU has contributed significantly to reducing hazardous pesticides in the market following the 1991 directive on placing plant protective products. This has seen over 500 active ingredients being withdrawn but not legally banned, and this explains why lower- and middle-income countries still serve as markets for some of the banned pesticides.

Pesticide Regulations in Kenya

The national government's role is to strike a balance between allowing the judicious use of pesticides in inevitable situations to promote crop health and food security and reducing adverse environmental and health effects. Therefore, several policy instruments are used by governments such as Kenya to ensure the balance is achieved. The registration and legislation of pesticides thus give room for regulating uses and availability. The national government can ban or restrict hazardous pesticides to specific crops, circumstances, and users. Budget allocation towards pesticide legislation to monitor pesticide residues in the food chain and research issues is also the government's role.

The PCPB, formed in 1984 under Cap 346 Laws of Kenya, is mandated to oversee pesticide manufacturing, importation, exportation, and use in Kenya. It aims at protecting humans' animals, and the environment from undesirable risks of pesticide use. The regulations thus cover policy-making and compliance with international conventions to which Kenya is a signatory (Lalah et al., 2022). The board issues import and export permits and assesses the quality, safety, and efficacy of pesticides and the suitability of premises. The board also advises various stakeholders on monitoring and standard observations in the pesticide industry, oversees the disposal of expired PCPs, keeps records of information and importation data, creates awareness, and prosecutes contraveners of the act. Only registered pesticides can be imported into the country for sale. Some institutions accredited by PCPB to approve new pesticide products in Kenya include the Ministry of Health, KEPHIS, the National Environment Management Authority, and the Agrochemicals Association of Kenya.

Conclusion

It is scientifically proven that the use of synthetic pesticides aids in increasing crop yields on farms; however, it comes with a higher cost as a result of the detrimental effects they have on human and environmental health. The side effects of the judicious use of pesticides are immense, leaving one with questions as to whether this should persist, considering the destructive impacts on the biosphere. The focus of this review was biased on the detrimental effects of pesticide use on the soil biosystems. However, there is a need to have an overall assessment of synthetic pesticides' benefits to the environment and the agricultural losses that may be encountered if they are not in use. Some crop pests and diseases can inevitably lead to dire food insecurities by reducing crop yields and contributing to increased deforestation in developing countries searching for alternative arable lands. This dilemma calls for a search for environment-friendly alternative agricultural practices (such as using pheromone traps) capable of reducing ecological risks associated with pests.

Pesticides do not directly interfere with soil fertility. However, they hinder long-term crop sustainability. For instance, fungicides are great at protecting crops against pathogenic fungi, but repeated use destroys beneficial mycorrhizal, whose function is to increase plant nutrient uptake. The recycling capacity of the soil by earthworms is hampered by copper fungicides and certain insecticides which kill the worms, decreasing soil fertility and crop yield. Using herbicides increases target crop yields but leads to biodiversity loss and an abundance of beneficial arthropods, aiding pollination. Insecticides used to decimate pests lead to the loss of parasitoids and predator populations in the food web, thus destabilizing the invertebrate communities and ultimately increasing pest populations. The long-term effect of this trophic disruption leads to futile efforts to contain the pest populations at unbearable costs. This issue could have been avoided by adopting integrated management practices. The indirect impacts of routine pesticide application are also evident in animals, birds, and other invertebrate species. Its therefore necessary to initiate changes in the policies, practices, and institutions that govern pesticide use to reconcile food security and biodiversity conservation.

Recommendations and future perspectives

The current review examines pesticide use's impacts on the ecosystems, focusing on soil biodiversity. Pesticide use is crucial in ensuring availability and accessibility to food supply across the globe. With Kenya being an agricultural country where over half of its population relies on crop agriculture for sustainability and Trans Nzoia County being the country's food basket, the likelihood of continuous reliance on pesticide use is inevitable. However, the long-term adverse effects of pesticide use on the soil ecosystem ring an alarm and call for urgent solutions by Kenya and the EU to reduce health and environmental risks. There is also a need to encourage a shift away from using HHPs with an increased momentum towards using fewer toxic alternatives such as biopesticides. It is evident that the demand and use of chemical pesticides have increased over the years, and farmers are yet to shift to alternative sustainable options. However, their use should be a last resort instead of the first-choice solution. Major food importers like the EU can incentivize the shift to environment-friendly alternatives. The author thus recommends;

- Collaboration among African countries in strengthening pesticide risk regulations
- Intentional collaboration with the Rotterdam Convention to strengthen programs that focus on capacity building regarding pesticides use

- Governments to ensure transparency and accessibility to regulatory risk data associated with pesticide use
- Encouraging rotational crop farming practices to cut down on repeated use of certain pesticides on the same farm over the years
- Investment in extension services and research activities on IPM and agroecology
- Educating farmers and farm workers on the proper handling and application of pesticides on the farm
- The need to put an end to the exportation and importation of products that have been banned in the EU
- Support of Kenya and other developing countries by EU and other developed countries in the reevaluation of the pesticide registration process ensuring alignment with the WHO/FAO code of conduct.

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