agriculture

MDPI

Article

Screening and Prioritization of Pesticide Application for Potential Human Health and Environmental Risks in Largescale Farms in Western Kenya

Zedekiah Odira Onyando [1,*], Elizabeth Omukunda [1], Patrick Okoth [1], Sandra Khatiebi [1], Solomon Omwoma [2], Peter Otieno [3], Odipo Osano [4] and Joseph Lalah [5]

[1] Department of Biological Sciences, Masinde Muliro University of Science and Technology, Kakamega P.O. Box 190-50100, Kenya
[2] Department of Physical Sciences, Jaramogi Oginga Odinga University of Science and Technology, Bondo P.O. Box 210-40601, Kenya
[3] Pest Control Products Board, Western Region, Kisumu P.O. Box 2757-40100, Kenya
[4] Department of Environmental Health, University of Eldoret, Eldoret P.O. Box 1125-30100, Kenya
[5] Department of Chemical Science, Technical University of Kenya, Nairobi P.O. Box 52428-00200, Kenya
* Correspondence: zonyando@mmust.ac.ke

Abstract: Pesticide application in agricultural and residential areas is a worldwide practice. However, human pesticide poisoning and environmental pollution through pesticide residues remain a challenge in the developing world. The present study investigated the intensity of pesticide application in large-scale farms in Trans-Nzoia County to screen and prioritize the pesticides for potential human health and environmental risks. A cross-sectional survey involving 348 farmers was conducted in the study area, and data was analyzed using SPSS. Environmental Exposure Potential (EEP) and Toxicity Potentials (TP) were analyzed from the Pesticide Properties Database (PPDB). Majority (99.4%) of the farms surveyed apply various pesticide classes that include: organophosphates (34.78%), neonicotinoids (15.22%), carbamates (10.87%), pyrethroids (10.87%), organochlorines (8.7%), triazoles (6.5%), copper-based (4.34%), avermectines (2.17%), triazines (2.17%), and amidines (2.17%), with the use of organic manures (26.3%). Despite the high prevalence of pesticide application, only 48.28% of farms conduct soil quality monitoring, 77.3% of whom do not have clear records and schedules for conducting periodic soil analyses. There was a strong positive correlation between the acreage of operation and the use of herbicides in weed management ($r = 0.77$; $p \leq 0.05$). In relation to degradation in the environment, 18.42% of the pesticides applied in the study area were persistent in soil sub-systems while 31.58% are persistent in water. Of the pesticides applied, 18.42% had high chances of bioconcentration in living tissues, 10.53% and 13.16% had the potential of contaminating groundwater and surface water resources, respectively. The ranked-order human toxicity potential associated with the used pesticides were teratogenicity (31.58%), neurotoxicity (28.95%), endocrine disruption (7.9%), carcinogenicity (7.9%), and mutagenicity (2.63%). However, 10.53% of the pesticides possess multiple toxicity potentials. Some farmers (53.70%) surveyed were not aware of the negative environmental impacts of pesticides with 59.50% having prior training on the use and handling of pesticides. Despite the availability of Personal Protective Equipment (PPEs) on larger farms, 31.9% of the farm workers do not adhere to their use during pesticide application. In conclusion, there is low awareness among farmers of human health and environmental risks associated with pesticide application. The study recommends training of farm managers, farm owners, and farm workers on pesticide handling and associated health and environmental effects.

Keywords: pesticides; human toxicity; bioaccumulation; environmental contamination; risks

check for updates

Citation: Onyando, Z.O.; Omukunda, E.; Okoth, P.; Khatiebi, S.; Omwoma, S.; Otieno, P.; Osano, O.; Lalah, J. Screening and Prioritization of Pesticide Application for Potential Human Health and Environmental Risks in Largescale Farms in Western Kenya. *Agriculture* **2023**, *13*, 1178. https://doi.org/10.3390/agriculture13061178

Academic Editors: Paula Pérez-Rodrígue and Diego Soto Gómez

Received: 17 September 2022
Revised: 5 November 2022
Accepted: 9 November 2022
Published: 31 May 2023

1. Introduction

Pesticides have been used for a long time [1] in many parts of the world in agricultural areas to manage crop pests, and in other non-agricultural establishments for various public health reasons, including control of disease-causing vectors and ornamental landscaping in residential and recreational areas [2–5]. Application of pesticide technology in agriculture was developed to increase yields by mitigating crop damages associated with outbreaks of pests and diseases [6–10]. Enhanced pesticide use has also been necessitated by the increased demand for food for the rapidly growing global human population after the mid-20th century [5]. Pesticide application is thus expected to continue rising in the future [4,11], as the global human population is expected to reach 9.1 billion by 2050 [12], most of which will be in the developing world. The commonly used pesticides in agricultural ecosystems include insecticides, herbicides, fungicides, and growth hormones, among others [1,6,8,11,13]. For instance, high synthetic fertilizer application is currently embraced by farmers as it increases grain yield by 68% above the organic manure per season [14]. Despite the high level of pesticide application in many parts of the world, their potential human health and ecosystem impacts have been overlooked [15]. Moreover, long-term monitoring studies have showed that continued use of pesticides can aggravate global warming by contributing to greenhouse gas emissions thus increasing carbon, nitrogen, and water footprints [16].

In Africa, the exact time when the use of pesticides begun is not well documented with some estimates reporting that these chemicals were first introduced to the continent between 1900 and 1920s [17]. Over time, pesticide application gained popularity among African farmers, particularly small-holder farmers as some were issued freely or sold at subsidized costs by governments through commodity boards and extension services [18]. The Kenyan government, just like other East African countries, supports various regional and national policies that diversify and modernize agricultural production in the face of evolving global climatic and economic circumstances with an aim of attaining environmental sustainability. Implementation of these policy initiatives, locally, nationally, or regionally has individually or cumulatively increased pesticide use in agro-ecosystems. This has made the agricultural sector the largest consumer of pesticides, accounting for 85% of pesticides produced globally [2]. For example, Kenya, imported 17,803 tons of pesticides valued at USD 128 million in 2018 [19], comprising of varying quantities of fertilizers, fungicides, insecticides, herbicides, fumigants, rodenticides, growth regulators, surfactants, and defoliators, while the annual national fertilizer consumption has been increasing at 1.6%, reaching 199 million tones by the end of 2019 [20]. Although misconceptions always designate only insecticides as pesticides, fungicides, rodenticides, herbicides, and other pest-control chemicals are also considered pesticides [21].

Regardless of the spatial disparities in pesticide application, pesticides have potential negative health and environmental effects, if not handled properly [1,4,22–27]. For instance, pesticide residues have been reported in various food sources including vegetables and beverages [6] making the use of pesticides a global public health problem in both developed and developing economies [28,29]. An estimated three million acute pesticide-related poisonings are reported annually, most of which are from developing countries [20,30]. Paradoxically, most of these pesticides are manufactured and sold in large volumes in the developed countries that consume over 85% of the global pesticide production [31]. High frequencies of pesticide poisoning in the developing world can be attributed to lack of training, inappropriate protective equipment, and weak enforcement of legislations governing pesticide use in the developing countries [32]. Numerous audits have reported inconsistencies in handling many pesticide products [11]. The EU indicated that many farmers do not follow the handling instructions as stipulated by the manufacturers. Farmers had limited knowledge on the health effects associated with pesticides, while some labels equally had deficiencies that could be addressed by extension workers. However, most of the pesticide toxicity-related investigations have been conducted in the developed countries [33] are not directly comparable to the tropical regions, due to the disparities in agronomic practices, climatic, and edaphic and human factors.

The screening of pesticides for potential human health and environmental exposure risks is key to identification of pesticides of greatest risk concerns hence helping in developing strategies for prevention of accidental poisoning, emergency planning and preparedness, detection, and alert [34]. Various exposure assessment techniques have been applied in different experimental studies including personal measurements, scenario-based assessments, and reconstructive analysis of biological measurements [35]. However, there is no scientific consensus on the diverse screening techniques available [36]. The present study used GUS (Groundwater Ubiquity Score) and Surface Water Mobility Index (SWMI) in analyzing environmental exposure and toxicity potential end points in characterizing the potential hazardous effects to humans and ecology with special focus on carcinogenicity, teratogenicity, endocrine disruption, mutagenicity, and neurotoxicity. This approach has been applied in other empirical studies in other parts of the world [37–39].

In Kenya, despite the strategies being put in place to curb pesticide pollution in the environment, recent studies have still reported alarming concentrations of pesticide residues in the environment [40–46]. Moreover, KEPHIS report of 2018 showed that there were still pesticide residues in vegetable samples collected from different parts of the country, with 10% of the samples having residue levels exceeding EU maximum allowable levels [47]. Nevertheless, there is paucity of data on the short-term and long-term human health and environmental impacts of pesticide exposure in Kenya. Over time, the government has developed strategies to mitigate environmental impacts of pesticides through policy and ratification to international conventions. For instance, Kenya ratified to the Stockholm Convention in May 2004 and developed a national implementation plan from 2007 and revised from 2014–2019 [48]. Despite national interventions, mismanagement of pesticides still poses significant threats to farmers, households, wider communities, and the environment in many parts of the world [49]. The present study was designed to identify the various types of pesticides applied by large-scale famers in the study area, investigate environmental exposure, and toxicity potentials of these pesticides to humans among large-scale famers in Trans-Nzoia County.

2. Materials and Methods

This study was conducted in Trans-Nzoia County in Western Kenya (Figure 1). The county lies approximately between latitudes 00°52′ and 10°18′ north of the equator and longitudes 034°38′ and 035°23′ east of the great Meridian with a total area of 2495.6 km^2. It has a total population of 818,757 distributed in five sub-counties: Kwanza, Endebes, Kiminini, Cheranganyi, and Saboti, and it is producing at least 5 million bags of maize annually from over 107,000 acres. It is divided into three major agroecological zones namely the Upper Highland Zones, Upper Midland Zones, and the Lower Highland Zones.

Trans-Nzoia County in Western Kenya was selected for this study because it is one of the regions in Kenya with favorable climate supporting large scale agriculture, which makes it the leading producer of maize in Kenya. Based on its prevailing climate and large-scale monocultures, the region provides a novel site for screening and prioritizing studies of agricultural pesticide application for potential human health and environmental risks. A reconnaissance was conducted to the study area and local authority's office (chief's office) in each ward to obtain permission and contacts of landowners who were to participate in the survey and plan field operations. The level of precision for the study was ±5% at a 95% confidence interval. Because the population of the farmers in the study area was unknown, sample size was determined according to the formula proposed by [50] as shown below.

$$n = \frac{(1.96)2 \times 0.5 \times 0.5)}{(0.05)2}$$

$$n = \frac{(\text{z score})2 \times pq}{(\text{Margin of error})2}$$

n = 385 respondents

where:

n: is the number of respondents to be involved in the study,
p: is the standard deviation, assumed to be 0.5,
q: is 1-p.

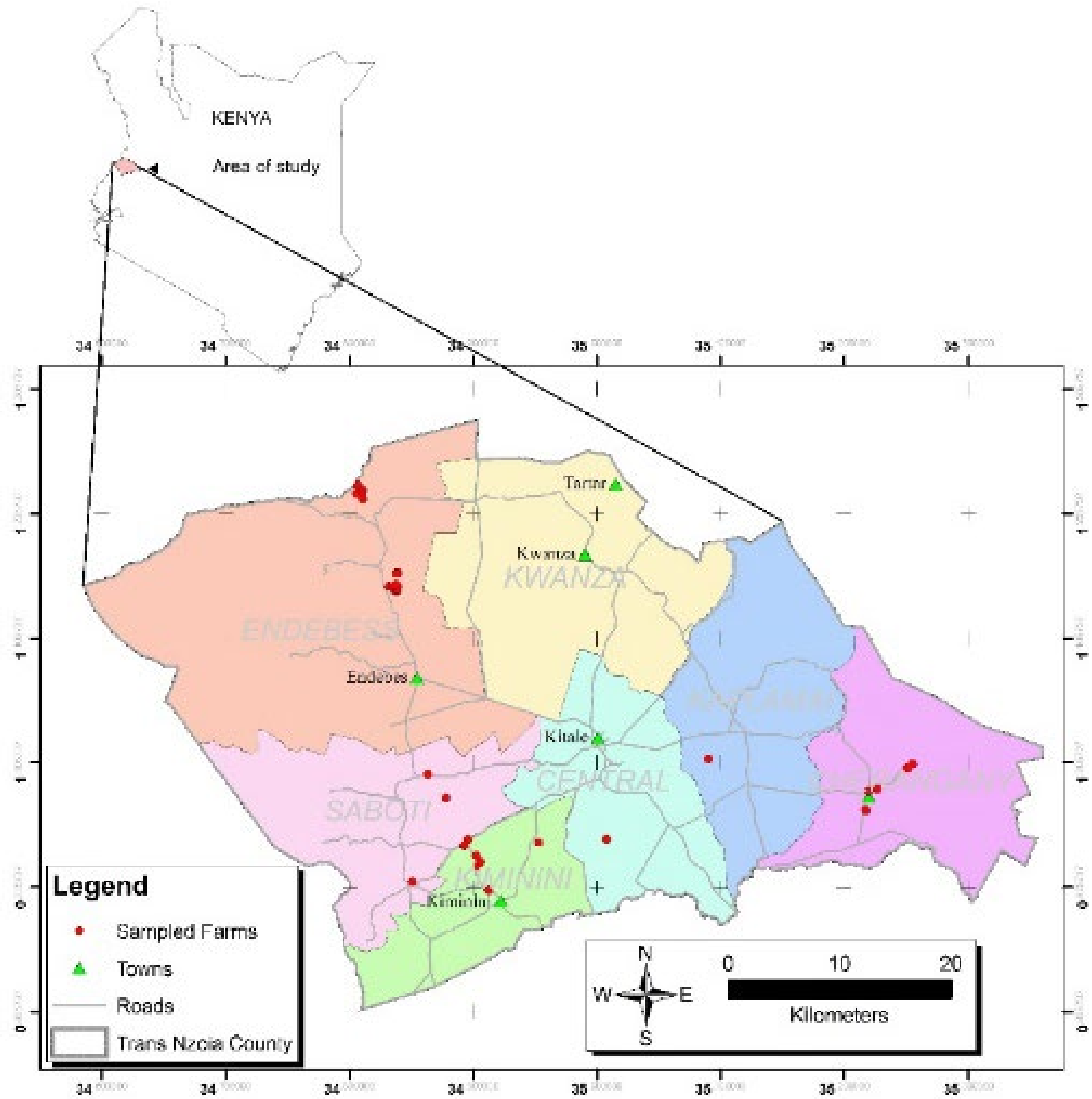

Figure 1. Digitized map of the study area.

A total of 385 farmers in five sub-counties were involved in the survey conducted between December 2019 and June 2021. Farm owners and/or managers of these farms were issued with consent forms. Farm owners/managers that consented to the survey were issued with questionnaires and engaged in structured interviews on the intensity of use of agrochemicals within their farms. The filled-in questionnaires were coded, and statistical data analyses were conducted using SPSS Version 20.0. The researchers also conducted an in-depth examination of the types of pesticides used, handling methods and disposal of empty containers of leftover pesticides.

Toxicity of the of the identified pesticides was analyzed based on their potential to persist in various environmental compartments, bioaccumulation potential and their possibility of causing harm to man, other mammals, aquatic organisms, soil fauna, such as earthworms, birds, and beneficial insects, such as bees, as indicated on the Pesticide Properties Database [31]. The main assumption that was made in this analysis was that humans and other organisms are more likely to be negatively exposed to pesticides that are more frequently applied without proper protective measures i.e., the use of Personal Protective Equipment (PPE) and uncontrolled sprays. Toxicity potential (TP) of each pesticide to humans and mammals was analyzed at four ranked levels ranging from 0–4 based on their ability to cause health problems such as endocrine disruption, neurotoxicity, teratogenicity, mutagenicity, and carcinogenicity. Those pesticides for which there is no documented data in relation to TP were ranked 0.

The Environmental Exposure Potential (EEP) of the identified pesticides was based on their ability to contaminate ground and surface water resources through leaching and surface run-off respectively. Groundwater contamination potential was determined from the pesticide's Groundwater Ubiquity Score (GUS) index [37]. This GUS index was applied in a logarithmic scale where those pesticides with GUS index below 1.8 had lower leaching potential while those with GUS index higher than 2.8 were classified to have high leaching potential. The potential of a pesticide to contaminate surface water resources was determined from Surface Water Mobility Index (SWMI). This was based on the fact that by applying the degree of mobility provided by standard pesticide properties database, it is possible to assess the chances of exposure through surface water sources [39]. Therefore, pesticides with SWMI tending towards 1 had higher potential to be carried by surface run-off.

3. Results

3.1. Farming and Cropping Systems

Majority of the respondents involved in the survey were males constituting 54% and while 46% of the respondents were females. The highest proportion (58.4%) of the respondents were aged 31–40 years, out of whom 46.6% had attained secondary level of education. In relation to training on the various strategies of handling pesticides, only 41.95% of the respondents had acquired training, while 58.05% had no training.

While some respondents engage in mixed farming (56.9%), some specialize in crop farming (43.1%). Various animals reared included cattle, poultry, sheep, and goats while the key plants were maize, sugarcane, horticultural crops, potatoes, hay, and coffee. Most of the respondents cited interdependence between crop and animal husbandry as the major reason behind mixed farming. Certain products from animal production units such as organic manure are used in boosting crop productivity. The participants involved in the study practiced farming for various durations ranging from one year to over 15 years. Only 15.81% had engaged in farming for five years or less.

Majority of the respondents (69.25%) practice farming for commercial purposes while only 8.27% for domestic purposes. However, 22.38% of the farmers undertake farming for both subsistence and commercial purposes. A limited proportion of the farmers engage in farming for reasons that could not be clearly stated. Various proportions of the produce are either sold or retained by the respondents for consumption. Most of the respondents (71.41%) market more than 75% of their produce while only 27.59% market less than 75% of the produce.

Farmers involved in the survey had different sizes of land on which they practice farming. Only 18.39% had farm sizes of over 30 acres while 33.62% of the respondents had farm with sizes ranging between 20–30 acres. However, certain farms like the Seven Agricultural Development Corporation (ADC) farms are in thousands of acres. Among the farms, both local and hybrid varieties of crops with various maturity periods are cultivated. Most of the respondents (87.89%) cultivate hybrid varieties while only 12.11% plant local varieties. Noted brands of maize varieties cultivated include those supplied by Western Seed Company (Kitale, Kenya), Seedco (Machakos, Kenya), and Kenya Seed Company (Eldoret, Kenya). The most dominant varieties and crop types cultivated in the region have a maturity period ranging between 3–9 months (92.2%). These crops included maize, horticultural crops, cereals, and potatoes. Only 3.4% and 1.9% of the famers grow crops with a maturity period of less than three months and more than one year respectively. The key crop types with longer maturity periods cultivated included bananas, cassava, grass, and sugarcane.

Despite the many varieties of the crops cultivated in the region, about half of the respondents (50.6%) plant their crops only in one season while 2.5% of them cultivate their crop in three seasons. The most dominant crop (maize) in the area is planted only once per year while some horticultural crops with irrigation are cultivated in two or more seasons. However, certain crops with long maturity periods such as grass and sugarcane could not easily be classified on the basis of seasonality.

There are various types of cropping systems practiced in the region, including intercropping and monoculture. Some of the farmers, however, practice both intercropping and monoculture on their farms. About 60.63% of the respondents practice monoculture while 39.08% practice intercropping. The most dominant monoculture crop in the region is maize. Commonly intercropped varieties include maize and beans/peas and millet/beans/peas in certain cases. Monoculture is common among the respondents with very large farms, ranging above 20 acres.

3.2. Soil Quality Monitoring and Management

There are existing strategies for managing soil quality and management of soil fertility among the farmers involved in the survey. Some of the soil fertility management practices include; fallowing, minimum tillage, intercropping, crop rotation, and use of agrochemicals. Conservation agriculture is also rapidly gaining momentum in the region. Slightly over half of the farm owners and managers (51.72%) do not undertake routine monitoring of soil quality, while 38.79% monitor soil quality. However, 8.91% of the respondents do not have any knowledge on the need for monitoring of soil quality within the farms.

Among the farmers who engage in monitoring of soil quality, 9.2% have employed experts within the farms in charge of soil monitoring while 29.02% utilize the services of extension officers. External soil analysis services are sourced from commercial laboratories located in the nearby towns, notably Kitale and Eldoret. However, 59.77% of farm owners do not have specific institutions where soil analysis services are procured. Various soil quality parameters that are monitored by the farmers include nutrient type and levels, pH, electrical conductivity, and pollutants. However, only 7.18% of the respondents had interest in analysis of all soil quality parameters. Besides, in 77.3% of the famers, there is no clear schedule for conducting soil analyses. Many managers and farm owners lack records of the previous soil analysis results.

The soil quality parameters that are of value to many farmers are pH and nutrient levels. Pollutant levels and soil microbiology are the least analyzed parameters in the region. About 0.29% of the farmers have interest in in understanding the soil pollution status, while only 0.58% of the farmers undertake monitoring of soil microbial status.

Traditional methods of soil fertility management that include fallowing and crop rotation are also applied by the farmers in the regions. Some (66.95%) of the farmers practise crop rotation while others (33.05%) do not. The commonly rotated crops include maize and sugarcane in certain sub-counties, maize and beans, and grass and maize, among others. Fallowing is not very common among the farmers in the region. Despite the value of this practice in natural restoration of soil nutrients, only 7.18% of the farmers practice fallowing while 89.08% do not. The most commonly used strategy for the management of soil fertility is through the use of agrochemicals and organic fertilizers. All the farmers involved in the survey apply various types of agrochemicals in their farms that include inorganic fertilizers and pesticides.

3.3. Intensity and Frequency of Pesticide Application

Majority of the farmers involved in the survey (99.4%) apply various pesticides at various stages of production that include insecticides, fungicides, herbicides, acaricides, preservatives, and growth hormones. In all the farms surveyed, inorganic fertilizers are applied at various stages of crop production. However, the use of organic manures is not a common practice among the large-scale farmers with only 26.3% of the farmers reporting that they use organic manures. The proportions of the respondents utilizing the various pesticides are as shown in Table 1.

Table 1. Types of pesticides used by farmers.

Pesticides	% Applying	% Not Applying	Total
Inorganic fertilizers	100.00	0.00	100.00
Fungicides	46.35	53.65	100.00
Insecticides	82.18	17.82	100.00
Growth hormones	43.10	56.90	100.00
Acaricides	48.56	51.44	100.00
Preservatives	100.00	0.00	100.00
Herbicides	79.48	20.52	100.00

The timing and frequency of pesticide applications during the growing seasons vary from one farm to another as shown in Figure 2. Majority of the farms (56.0%) apply the pesticides twice between planting and harvesting.

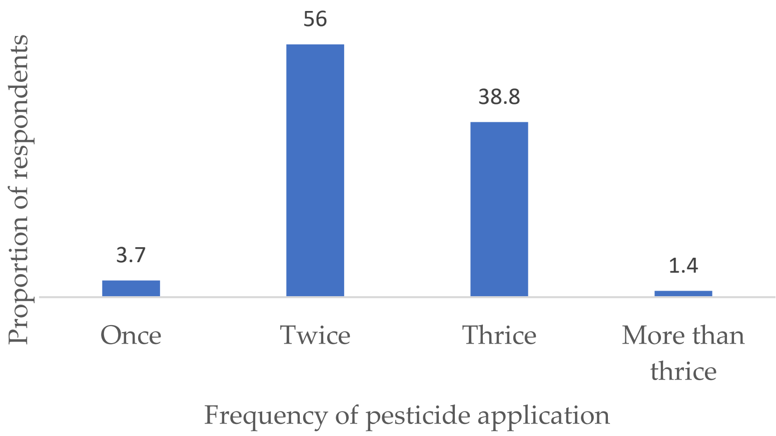

Figure 2. The frequency of pesticide application during growing season.

3.4. Types of Pesticides Applied in Large-Scale Farms

There are various pesticides applied by the farmers as illustrated in Table 2. All the respondents utilize inorganic fertilizers for various purposes including planting and top-dressing. Phosphatic, NPK, nitrogenous, and urea fertilizers from different manufacturers are applied in various quantities based on the farmers' financial ability to purchase the products and the perceived effect of the input on the output. There is no common standard on the amount and the number of times the fertilizers are applied on the farms.

In relation to the use of herbicides, there is a positive correlation between the acreage of operation and the use of herbicides in weed management ($r = 0.77$, $n = 348$, $p \leq 0.05$). Large-scale famers with over 30 hectares mainly apply herbicides for weed management. The most commonly applied pesticides include; carbendazim (32.94%), imidacloprid (23.58%), diazinon (20.40%). S-metachlor (28.17%), mesotrione (28.17%), and copper-oxychloride (13.49%), shown in Table 2.

The choice of the preferred pesticides applied in the farm depends on a number of factors as shown in Figure 3. These factors include: cost, ease of usage, effectiveness, availability, and quantity of the specific brand (Figure 3). However, the effectiveness (31.5%) of the pesticide is the most common factor that influences its choice for application, while cost (5.7%) is the least determining factor.

Table 2. Proportions of the commonly used pesticides by large-scale famers.

Fungicides	% Proportions	Insecticides	% Proportion	Herbicides	% Proportion	Acaricides	% Proportion
thiomethoxam	2.12						
copper oxychloride	13.49						
azoxystrobin	5.17	imidacloprid	23.58				
difenoconazole	5.17	λ-cyhalothrin	4.07				
carbendazim	32.94	diazinon	20.40				
β-cyfluthrin	1.44	α-cypermethrin	5.46				
chlorpyrifos	1.44	chlorpyrifos	10.60				
fludioxonil	2.33	mefenoxam	5.75	S-Metachlor	28.17		
mancozeb	2.23	profenophos	5.75	mesotrione	13.88		
epoxiconazole	17.62	β-cyfluthrin	2.65	terbuthylazine	1.72		
tebuconazole	0.58	β-cyahalothrin	10.86	acetochlor	19.11		
trifloxystrobin	0.58	lufemuron	0.29	Atrazine	1.43		
propoxur	1.15	actamiprid	0.29	bipyridylium	2.14		
imidacloprid	0.10	carbosulfan	2.01	lambda-cyhalothrin	3.43		
cypermethrin	4.13	abamectin	7.14	Glyphosate	25.52		
triazophos	4.13	carbaryl	4.02	Bentazon	2.30	Cypermethrin	21.84
λ-cyhalothrin	4.13	acephate	1.44	Glycine	1.15	Chlorpyrifos	21.84
acetamiprid	1.15	heptachlor	1.15	chlorimuron ethyl	1.15	Amitraz	56.32

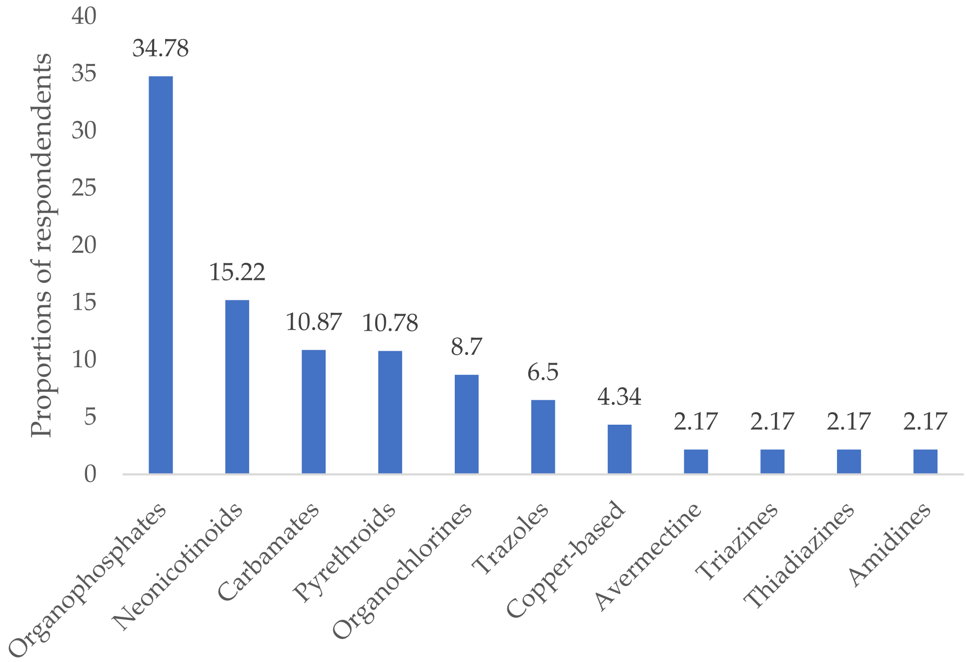

Figure 3. Proportions of pesticide classes applied by large-scale farm.

The choice of the preferred pesticides applied in the farm depends on number of factors as shown in Figure 4. These factors include cost, ease of usage, effectiveness, availability, and quantity of the specific brand (Figure 4). However, the effectiveness of the pesticide is the most common factor influencing the effectiveness of the pesticide to be applied (31.5%) while cost is the least determining factor (5.7%).

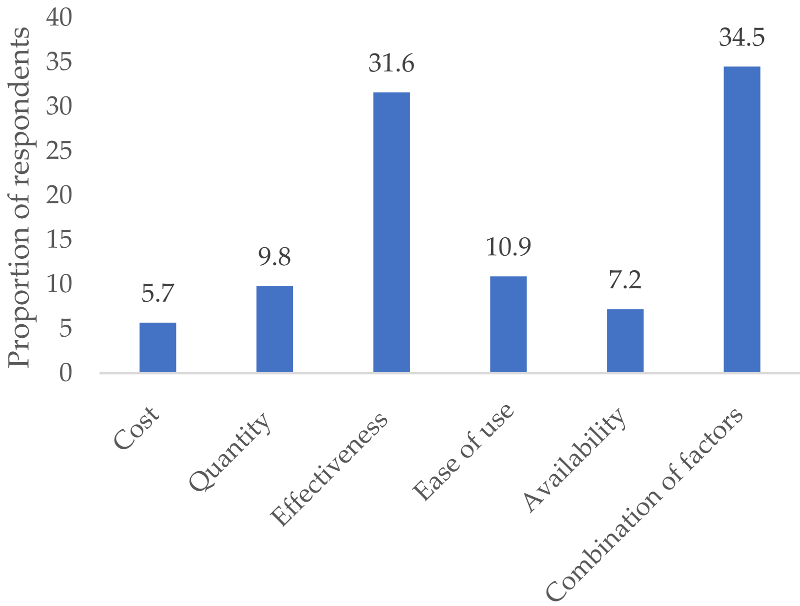

Figure 4. Factors influencing the choice of preferred pesticides.

3.5. Environmental Exposure Potential of Pesticide Application

Analysis of environmental exposure potential of the various pesticides identified are as summarized in Table 3. Pesticides applied by famers in the study area had different levels of persistence in soil and aquatic ecosystems. While 18.42% were not persistent in soil systems, 31.58% were potentially persistent in aquatic ecosystems. Due to ubiquity and mobility, 10.53% and 13.16% of the pesticides were highly transferable to ground and surface water resources, respectively. However, 18.42% of the used pesticides had higher potentials for bioconcentration in the living tissues. These included acetamiprid, heptachlor, amitraz, chlorimuron ethyl, azoxystrobin, and copper oxychloride.

In relation to impact on non-target animals, the pesticides applied have varying degrees of toxicity to mammals, birds, aquatic invertebrates, and the soil-dwelling earthworms, as illustrated in Figure 5. Most of the pesticides (39.47%) are highly toxic to aquatic invertebrates, while 18.84% are highly toxic to earthworms.

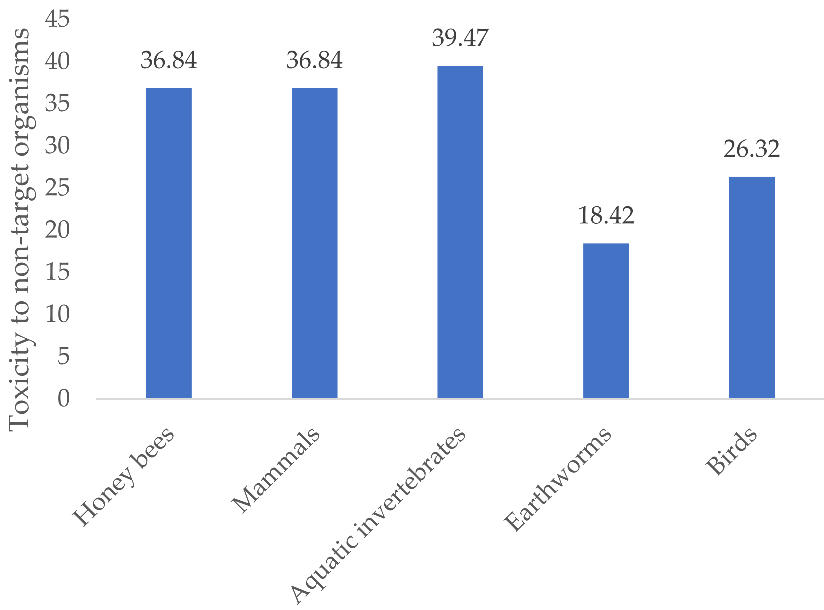

Figure 5. Proportions of pesticides highly toxic to non-target organisms.

Table 3. Environmental Exposure Potentials of the commonly used pesticides (Key: 0-No data; 1-No effect; 2-Less; 3-Moderate; 4-High; symbol * means property of interest; Source: Lewis et al. 2016).

Pesticides	Persistence in		Solubility	Volatility	Ease of Transfer		Potentially Toxic to					Bioaccumulation Ease
	Soil	Water			GUS Index	SWMI Score	Birds	Mammals	Aquatic Invertebrates	Bees	Earthworms	
thiomethoxam	1	3	4	1	4	4 *	4 *	4 *	4 *	4 *	1	2
copper oxychloride	4 *	4 *	2	2	0	0	3	3	3	3	3	4 *
azoxystrobin	3	3	2	1	3	3	3	2	3	3	3	3 *
difenoconazole	3	3	2	3	2	3	3	3	3	3	3	3
carbendazim	3	4 *	3	4 *	4 *	3	1	2	3	3	4 *	1
β-cyfluthrin	1	4	2	3	2	1	4	4	4 *	4 *	3	2
chlorpyrifos	3 *	1	2	3	2	2	4 *	4 *	4 *	4 *	3	2
fludioxonil	4 *	3	2	2	2	1	3	2	3	2	3	2
mancozeb	1	3	2	3	2	3	3	2	4 *	2	3	2
epoxiconazole	3	3	2	3	3	3	3	4 *	4 *	4 *	4 *	1
tebuconazole	3	4 *	2	2	3	3	3	4	3	3	3	2
trifloxystrobin	1	1	2	2	2	2	4	2	4 *	3	2	2
Propoxur	4 *	2	4 *	4 *	4 *	4 *	4 *	4 *	4 *	4 *	4 *	2
Triazophos	3	4 *	2	2	2	3	4	4	4	3	3	2
acetamiprid	1	4 *	4 *	4 *	1	4 *	4 *	3 *	3 *	0	4 *	4 *
imidacloprid	4 *	4 *	4 *	1	4 *	3	4 *	4 *	3	4 *	3	2
λ-cyhalothrin	1	1	2	4	2	1	3	4	4 *	4 *	3	2
diazinon	1	4 *	3	4 *	2	3	4 *	3	4 *	3	3	2
α-cypermethrin	1	4 *	3	3	1	4 *	1	4 *	4 *	4 *	3	2
profenophos	1	4 *	2	2	2	3	4 *	3	3	4 *	4 *	2
s-metachlor	3	3	3	2	3	3	2	2	3	3	3	2
lufemuron	1	3	1	2	2	2	3	2	3	2	3	4 *
carbosulfan	1	1	2	1	2	3	3	3	4 *	4 *	4 *	2
carbaryl	1	1	2	4 *	3	3	3	4 *	2	4 *	4 *	2
acephate	1	1	4	4	2	3	2	3	2	2	2	2
heptachlor	4 *	1	2	4 *	2	1	3	4 *	4 *	4 *	3	3 *
mesotrione	2	3	4	2	2	3	2	4 *	2	2	3	2
terbuthylazine	3	4	2	2	2	3	3	3	3	3	3	2
acetochlor	1	4	3	3	3	3	3	4 *	3	3	3	2
atrazine	3	3	2	3	3	3	2	3	3	3	3	1
glyphosate	1	2	3	3	1	3	3	3	3	3	3	2
bentazon	2	3	4 *	4 *	3	4 *	3	3	3	3	3	2
chlorimuron ethyl	3	2	3	1	3	3	1	2	1	3	1	4 *
amitraz	4 *	1	1	2	2	2	3	3	3	3	3	3 *
cypermethrin	3	3	2	3	1	2	2	3	4 *	4 *	3	2
malathion	4 *	4 *	3	3	2	3	3	3	4 *	4 *	1	2

3.6. Human Toxicity Potentials of the Pesticides Applied in the Study Area

Analysis of the toxicity potentials from the pesticide properties database showed that all the pesticides applied in the study area are potentially harmful to human health if not properly used. The proportions of the pesticides classified under different toxicity potentials include endocrine disruption, neurotoxicity, teratogenicity, mutagenicity, and carcinogenicity as summarized in Table 4. Some pesticides (10.53%) had the potential for more than one human toxicity problem.

Table 4. Human toxicity potentials of pesticides applied in the study area.

Toxicity Potential Class	% Proportion of Pesticides	Examples
Multiple toxicity potential	10.53	mancozeb, acephate, heptachlor, epoxiconazole
Endocrine disruption	7.90	mancozeb, carbaryl, acephate
Carcinogenicity	7.90	carbaryl, heptachlor, epoxiconazole
Mutagenicity	2.63	Acetachlor
Teratogenicity	31.58	cabendazim, alpha-cypermethrin, chlorpyrifos, carbaryl, heptachlor, acetochlor, imidachloprid, epoxiconazole, tebuconazole, influxystrobin, mancozeb, S-metachlor
Neurotoxicity	28.95	acephate, chlorpyrifos, diazinon, beta cyfluthrin, amitraz, hepachlor, meta-cyhlothrin, malathion, profeofos, triazophos, mesotrione

3.7. Handling and Awareness of Potential Environmental Impacts of Pesticides

Despite the continued use of pesticides by farmers in the region, 53.7% of the respondents are not aware of the negative environmental impacts of continued use of these inputs. All the larger farms surveyed have invested in personal protective equipment (PPEs) that are used by the farm workers during the application of agrochemicals. These Personal Protective Equipment (PPEs) include those that protect the workers from harmful fumes, gases, and corrosive solutions, among others. However, only 68.1% of the respondents regularly use the PPEs while doing major operations.

A small percentage of the respondents (59.5%) have prior training on the application and handling of pesticides while 0.3% were not aware of the existence of such training opportunities. Many farm workers involved in the actual pesticide application in the farms have limited information on the chemical composition and active ingredients of the products. This is further illustrated in the disposal methods of the packages or containers in which these products are purchased. Various disposal options are applied by the farm workers, including destruction/puncturing, return to suppliers, and re-use for other purposes. The proportions of the respondents applying the various disposal methods are as illustrated in Figure 6.

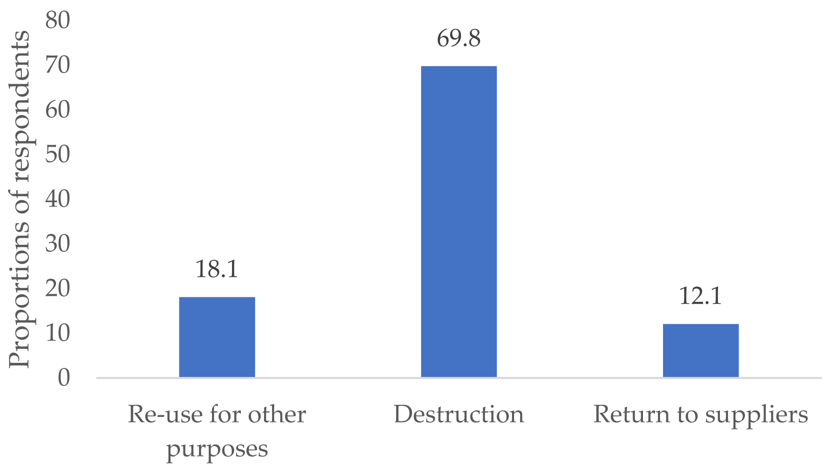

Figure 6. The disposal options of pesticide packages and containers.

Majority of farms surveyed (69.8%) prefer destruction and puncturing as the best method for disposing of used agrochemical containers. This involves destroying the pesticide container and dumping them at a specific site. Punctured containers are less attractive and hence not preferred for reuse. However, in 18.1% of the farms, selected containers are reused for other purposes while 12.1% of the farms return them to the suppliers. In most of the surveyed farms, large piles of previously used pesticide containers could be seen in specific locations within the farm stores. Most of these packages and containers are those that are perceived to be less dangerous to human and animal health.

4. Discussion

Agriculture is one of the sources of livelihood in Kenya, employing many rural communities [29,51]. In Kenya, Trans-Nzoia County has been known for its high agricultural potential spanning from the colonial period due to its favorable prevailing climatic conditions and edaphic characteristics that support large-scale production of different animal and crop varieties that include dairy, cereal, and other cash crop production [52]. Most of the farms were formerly owned by the white colonists before independence, hence the reason why most of the farms surveyed had higher acreages under commercial production. Even previously smaller farms have been expanded over the years due to the increased demand for food supplies. This is in line with global trajectory of rapid expansion of agricultural systems through conversion of natural or native vegetation to cultivated agricultural landscapes over the past few centuries [53] and that currently, over one third of the world's land is under agriculture [54]. Most of the large farms surveyed are privately owned, apart from a few that are owned by the government through the Agricultural Development Corporation (ADC). Due to the existence of limited data on soil properties in areas of low intensity farming [55], large-scale farming catchments provide novel sites for studying pesticide application and associated health and environmental impacts.

Continuous cultivation in large-scale farming catchments, most of the structurally fragile agricultural soils have been depleted of essential nutrients [55], polluted [51,56], and exposed to harsh weather conditions leaving little or no time for natural restoration of soil quality. Sustaining crop yields among farms have involved the combination of traditional methods and use of pesticides. However, traditional soil fertility management practices, such as crop rotation, mixed farming, fallowing, and intercropping, are perceived by farmers to have not significantly impacted the restoration of soil fertility. Crop rotation, despite its low prevalence in the study area, is one of the key practices in organic farming. Organic farming has been advocated for due to its potential to maintain soil fertility and structure by enhancing soil ecosystem services, carbon sequestration, organic matter content, and controlling some pests, weeds, and diseases. For example, in Thailand, a comparative study on the impacts conventional (CF) and organic (OF) rice farming on soil organic carbon showed that even though climate change will negatively impact on soil organic carbon (SOC), organic farming will have minimum negative effects compared to conventional rice farming [57]. From the 20th century, the rotation of cereals and legumes has been understood to boost soil nitrogen and organic matter content [58]. Higher soil organic carbon levels were reported [59] in seven years of treatments compared to where rotation had been done for two years. However, with increased global industrialization that increased industrial sources of nitrogen and development of pesticide technology for controlling pests, crop rotation has become less popular among farmers [60]. Even in temperate regions, crop rotation has been declining since the 1950s as monocultures and short rotations started being practiced [61]. Fallowing is perceived as economically unproductive with only 10.92% of the farms embracing it. This is despite the fact that fallowing, if well practiced, facilitates stabilization of crop production through natural partial compensation of nutrients [62] by restoring soil organic matter content [55] and allowing decomposition of both above and below-ground plant biomass [58], hence restoring soil fertility in the next season. Decreasing farm sizes due to rising human population and competing land uses in the study area have raised the demand for agricultural land, making fallowing less economically feasible.

Majority (99.4%) of the farmers surveyed routinely apply pesticides to manage emerging crop pests, thus boosting productivity (Table 1). At the global scale, there is an estimated 70,000 pest species comprising mites and insects, plant pathogens, and weeds that account for 14%, 13%, and 13%, respectively, of crop damage [63]. Most of the large-scale farmers have embraced the use of chemical pesticides for controlling pests such as rodents, insects, fungi, and weeds, hence helping to enhance crop performance, thus boosting productivity. Due to enhanced crop performance resulting from pesticide use, many farm owners pay little attention to monitoring soil quality with only 38.79% monitoring soil physicochemical status, while 8.91% of the respondents do not have any knowledge on the need for routine monitoring of soil quality. Soil quality, an integration of the physical, chemical, and biological properties [64] in the study area is not documented despite the various land management systems practiced by the farms surveyed. This knowledge gap inevitably means that the edaphic and biotic concentration levels of persistent pesticides residues and their impacts on soil physicochemical conditions in the study area remains poorly understood. However, soil quality monitoring is an important exercise that helps in mitigating negative environmental and health impacts of agricultural contaminants due to absorption by cultivated crops [65]. Human exposure to pesticides and heavy metals through consumption of edible plants grown in contaminated soils has been a global concern due to potential to cause toxicity and disease in humans and animals. Maize grain harvested from soils contaminated with heavy metal has been found not fit for human consumption due to high degree of exposure to heavy metal contamination [66].

Among the conventional soil quality parameters, nutrient levels are the main parameter of interest tested by famers. This is despite the fact that nutrient levels are not the only indicator of soil ecosystem health and fertility. All biological and physical characteristics of the soil are important in soil fertility assessments. Pesticide overload in soils may influence other soil chemical characteristics like pH that directly affect the mobility and adsorption of other pollutants such as heavy metals. Soil acidification has been reported to increase mobility of Cd, Zn, and Pb in the order of Cd > Zn > Pb [67]. It is reported that apart from Copper, the combined effect of pH and organic matter strongly influenced availability of heavy metals, and that Cadmium uptake in maize plant issues depended on soil pH and organic matter. Application of inorganic fertilizers is not regulated in many of the farms surveyed with the frequency only being determined by the nature of the crop and financial ability of the famers to purchase the input. Many farmers believe that crop yields are directly proportional to the amount of fertilizer applied. Organic manures, despite the high nutrient levels and limited environmental harm, are not commonly used by the farmers. Only 26.3% of the farms surveyed embrace the use of these manures. Application of animal waste as manure reduces environmental contamination from precursor wastes, minimize waste treatment costs, and boosts agricultural productivity. Organic fertilizers also have high organic matter content that provides energy for active and healthy soil microbial environment [68] that stabilize nutrients and makes them available. Many previous studies have proved that microbial activities within the soil improve soil nutrient levels. When integrated in soil sub-system, they are important in determining nutrient cycling, thus biogeochemical cycles. RDA analysis by [69] also reported that soil bacterial community diversity in fish-rice faming integration was positively correlated with some important soil properties. Some bacterial communities also facilitate degradation of pesticides hence promoting soil ecosystem health. For example, the *Bacillus* species and the *Staphylococcus* species isolated from pineapple and sugarcane cultivated soils in Kenya were reported to enhance degradation of hexazinone [70]. However, the collection, transport and application of manure is viewed as being labor-intensive and time-consuming by some farmers in the study area. Besides, it is perceived that manure is crop-selective and does not have immediate impact on the soil quality due to low or slow rates of decomposition.

Despite the positive impact of inorganic fertilizers on crop yields, overuse of these inputs can cause environmental pollution [71]. For example, excessive application of fertilizers to waterlogged soils potentially leads to their infiltration to groundwater while some fertilizer residues are carried by storm waters to aquatic ecosystems, thus creating surface water pollution. Nitrate (NO_3^-) from the application of nitrogenous fertilizers has high leaching potentials to groundwater making agriculturally-induced nitrate loading to groundwater sources a global problem [72]. In China, for example, over-application of chemical fertilizers to increase crop yields resulted in elevated NO_3^- levels. Over 50% of groundwater samples collected and analyzed from agricultural fields, even in areas with deeper groundwater, showed high concentrations of up to 300 mg L^{-1} of nitrates [73]. Infiltration and surface water transfer of fertilizer residues can be very rapid in the study area based on the high rainfall amounts (1000 mm to 1700 mm) received in the region and topography that facilitates overland run-off.

Many factors influence the choice of pesticides brand used by the farmers including availability, ease of use, cost, and effectiveness of the pesticide (Figure 4). However, effectiveness in controlling the target pests in large-scale farms remains the key factor determining the choice of the pesticide brand applied in the agroecosystems. This explains the high frequencies of the use of the organophosphates, pyrethroids, and neonicotinoid pesticides (Figure 3). Organophosphate pesticides, which are usually esters of ortho-trio and pyrophosphoric acids, have been adopted in pest management due to their high effectiveness as contact pesticides and perceived low persistence in the environment. Although organophosphate and carbamate pesticides are considered less persistent in the environment compared to organochlorines, most of them are partially harmful to humans if not well handled. Pyrethroids, despite having low human health impacts, pose more danger to surface and groundwater pollution, and are toxic to insects which have other important ecological roles to play in ecosystems. Trans-Nzoia County being found in a tropical region with a high diversity of insects that act as pollinators and dispersers within the agricultural ecosystems. With pyrethroid-based pesticides being used (10.87%), 36% of which are potentially toxic to honey bees (Figure 5; Table 3), the population of these important pollinators may be affected by improper application of the pesticides. In some cases, long-term exposure of honey bees to pesticides may initiate genetic changes and co-evolution among plant pollinator species. For example, it is revealed that pyrethroid insecticides are commonly used in controlling mosquito vectors that cause malaria disease [74]. However, intensive use of the pesticide reduces its effectiveness in controlling the vector due to development of resistance. It is recently reported that imidacloprid, chlorpyrifos, and esfenvalerate in nectar, deltamethrin in nectar and pollen pose potential acute risk to honey bees [75].

There is high probability of deposition of pesticide residues in the environmental compartments including surface and ground water due to lack of clear guidelines regarding their application. About 13.16% and 10.53% of the pesticides used are having higher potentials of being transported to surface water and groundwater, respectively (Table 3). Therefore, surface and groundwater resources in the study area are more susceptible to pollution. Five (5) pesticides applied in the study area have high GUS hence high ease of groundwater contamination including thiomethoxam, carbendazim, propoxur, imidacloprid and bentazon. However, five pesticides, including Thiomethoxam, Triazophos, Propuxur, alpha cypermethrin, and Bentazon, have high SWMI, thus high chances of pollution of surface water resources. From the survey, nine pesticides are also not easily degraded in water medium, implying they may have long-term effects in aquatic ecosystems. This poses a higher risk to aquatic invertebrates as 39.7% are also highly toxic to aquatic invertebrates. The soil-water transfer of such pesticide residues can be enhanced by the prevailing climatic patterns in the study area. For example, high annual rainfall ranging between 1000 mm to 1700 mm received in the Western parts of Endebess, Saboti and Kiminini Sub Counties and Northwestern parts of Cherang'any Sub County can promote leaching of pesticide residues to groundwater and transport to surface waters by surface run-off. In

India, it was reported that river Deomoni of the Terai region is polluted with organochlorine and organophosphate pesticides from runoffs that affect aquatic environment, hence potential negative effects on aquatic organisms and humans [76].

High persistence potentials of pesticides residues and their degradation products in soil sub-systems implies long-term ecological effects in agricultural lands. Six pesticides used by farmers in the study area have high edaphic persistence rate. Cool temperature with mean maximum temperatures ranging between 23.4–28.4 °C and mean minimum temperatures ranging between 11.0–13.5 °C recorded in February and January respectively may facilitate adsorption of some of the pesticide residues. Many previous studies have reported the existence of residues in the environment many years after their application have been banned [77,78]. For example, a study by [78] did not detect heptachlor at the selected sites of River Nyando watershed but its degradation product, heptachlor epoxide, was detected at the same sites. Accumulation of pesticides and their degradation products in agricultural soils may affect soil-dwelling fauna, most of which play important roles in controlling soil physicochemical qualities. About 18.84% of pesticides used in the study area are highly toxic to earthworms, which are important ecosystem engineers. 18.42% of the pesticides applied by farmers in the study area have high potential of bioconcentration, most of which tend to be hydrophobic thus persisting in the animal tissues, hampering normal functioning of biological systems [79]. Metachlor and acetachlor, for example, have been banned in some countries due to their perceived persistence in biological systems. These pesticides are, however, still being used at some of the surveyed farms. Stockholm Convention was an international endeavour that banned the production, use, and emissions of Persistent Organic Pollutants (POPs), including organochlorines. Among the banned pesticides are the organochlorine pesticides (OCPs) including dichlorodiphenyltrichloroethanes (DDTs), hexachlorocyclohexanes (HCHs), and endosulfans.

Awareness on the environmental and health impacts of pesticides remains important at local and national levels. However, many farm owners, managers, and workers (40.5%) still have limited information on the chemical composition and active ingredients of the pesticides applied in the farms. With 53.7% of the farm owners and managers not aware of the negative environmental impacts of pesticides, there is a high risk of indiscriminate pesticide application and poisoning among farm workers. This is coupled with the fact that despite farm owners investing in PPEs, only 68.1% of farm workers embrace regular use of PPEs during pesticide handling and application. Most of the workers are employed based not on academic training but the capacity to accomplish certain key activities on the farms. This is why in 18.1% of the farms surveyed, have agrochemical containers still piled up at the farm stores and even reused for other purposes. This further explains the irregular use of PPEs by farm workers during routine operations, making workers vulnerable to pesticide poisoning through respiratory, dermal, and gastrointestinal pathways. However, PPEs like face shields, goggles, aprons, and respirators are very important in protecting farm workers from direct contact with pesticides [80]. While investigating pesticide use practices among smallholder vegetable farmers in Ethiopian Central Rift Valley, it was found that many farmers apply pesticides and dispose of pesticide containers without considering the recommended safety measures [81].

Analysis from the PPD revealed that the pesticides applied in the study area belonged to various toxicity potential classes (Table 4). Many farm workers are thus exposed to various human health problems associated with pesticide exposure including neurotoxicity, teratogenicity, carcinogenicity, endocrine disruption, and mutagenicity. Glyphosate-Based Herbicides (GBHs) that have been used extensively in various parts of the world and have attracted a lot of international attention due to their perceived negative effect on the environment and human population [82]. Many of the GBHs have been banned in the developed world due to the perceived carcinogenicity and negative effects on neurologic, gastroenteric, endocrine, and reproductive systems. For example, in mammals, empirical research has shown that glyphosate can interfere with hormonal functioning, especially disrupting steroidogenesis. These GBHs also have the potential to cause Ca^{2+} overload, hence redox imbalance [83], and some cytotoxicity as they have traces of certain heavy metals, such as arsenic, chromium, cobalt, lead and nickel. Moreover, 10.53% of the pesticides used including mancozeb, acephate, heptachlor, and epoxiconazole have the potential to cause multiple human toxicity problems despite their high usage frequency in the study area (Table 2). There is a need for the training of farm owners and workers on the negative human and environmental risks associated with pesticide exposure. This can be achieved through capacity building of the workers through training workshops, mass media, and robust extension services coordinated by the Ministry of Agriculture at the national level, and Department of Agriculture at the county level.

5. Conclusions

In conclusion, majority of large-scale farmers in the study areas practice mixed farming for commercial purposes. Most of the crops are cultivated in one season and monoculture is the most commonly practiced cropping system. Various strategies are employed by the farmers controlling crop pests to boost productivity with the use of pesticides being the most dominant strategy. Monitoring of soil quality conditions is not a common practice among farmers in the study area. Most farmers use pesticides in controlling crop pest for higher yields, despite their lack of knowledge on the environmental impacts and the chemical composition of their preferred brands.

Environmental exposure analysis showed that some pesticides used in the study area have high chances of contaminating surface and groundwater resources if not properly used, while others can persist in soil and aqueous media posing long-term threats to aquatic invertebrates and soil dwelling organisms such as earthworms. Among the faunal groups that are commonly considered in environmental exposure analysis, mammals, birds, honeybees, and aquatic invertebrates are the most susceptible to pesticide exposure, as higher proportions of the pesticides applied in the study area are highly toxic to them. However, only 18.42% of the surveyed pesticides are highly toxic to earthworms, demonstrating their high tolerance to environmental pollution.

Human toxicity potential analysis showed that 10.53% of pesticides applied in the study area have the potential to cause multiple human health problems. However, the rank-order of human toxicity potentials of the surveyed pesticides is: teratogenicity > neurotoxicity > carcinogenicity > endocrine disruption > mutagenicity. Lack of knowledge on the environmental and human health risks associated with pesticide use, limited training opportunities, infrequent use of PPEs, and poor disposal methods expose farm workers to potential pesticide poisoning.

The study recommends that there is a need to intensify extension services in the study area, encourage more farm owners and managers to attend training on handling of pesticides, and develop policies that regulate the use of certain pesticides by famers in the study area.

Author Contributions: Conceptualization, Z.O.O., E.O. and J.L.; methodology, Z.O.O., E.O., S.O. and J.L.; software, P.O. (Patrick Okoth), S.K. and S.O.; validation, Z.O.O., E.O. and J.L.; formal analysis, Z.O.O. and P.O. (Patrick Okoth); writing—original draft preparation, Z.O.O., E.O. and J.L.; writing—review and editing, Z.O.O. and E.O.; visualization, P.O. (Peter Otieno); supervision, E.O. and J.L.; project administration, Z.O.O., E.O. and J.L.; funding acquisition, E.O., O.O., S.O., P.O. (Peter Otieno) and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: The National Research Fund, NRF/2018 10000000, provided funding for field work and laboratory analysis for this research. There was no funding for publication and other activities after the laboratory works. The study was conducted in accordance with the Declaration of Helsinki, and approved by the institutional Ethics Review Board of Masinde Muliro University of Science and Technology.

Data Availability Statement: Most of the data relating to the properties of the identified pesticides were obtained from the Pesticide Properties Database PDP available at http://sitem.herts.ac.uk/aeru/ppdb/.

Acknowledgments: We would like to thank the Department of Agriculture in Endebes Sub-County for their help during data collection especially in farm identification. We are also grateful to the staff at the Agricultural Development Corporation (ADC), Kitale Branch and at their various farm managers especially at Suam and Namandala farms who greatly assisted us during the survey.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Pandya, I.Y. Pesticides and their applications in agriculture. *Asian J. Appl. Sci. Technol.* **2018**, *2*, 894–900.
2. Kim, K.; Ehsanul, K.; Shamin, A.J. Exposure to pesticides and associated human health effects. *Sci. Total Environ.* **2017**, *575*, 525–535. [PubMed]
3. Gyawali, K. Pesticide Uses and its Effects on Public Health and Environment. *J. Health Promot.* **2018**, *6*, 28–37.
4. Sharma, A.; Vinod, K.; Babar, S.; Mohsin, T.; Gagan, P.; Singh, S.; Neha, H.; Sukhmeen, K.; Poonam, Y.; Aditi, S.; et al. Worldwide pesticide usage and its impacts on ecosystem. *App. Sci.* **2019**, *1*, 1446. [CrossRef]
5. Tudi, M.; Huada, D.R.; Jia, L.; Ross, S.; Des, C.; Cordia, C.; Dung, T.P. Agriculture Development, Pesticide Application and Its Impact on the Environment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1112. [CrossRef] [PubMed]
6. Nicolopoulou, S.P.; Maipas, S.; Kotampasi, C.; Stamatis, P.; Hens, L. Chemical pesticides and human health: The urgent need for a new concept in agriculture. *Front. Public Health* **2016**, *4*, 148.
7. Jallow, M.F.A.; Dawood, G.A.; Mohammed, S.A.; Vimala, Y.D.; Binson, M.T. Pesticide Knowledge and Safety Practices among Farm Workers in Kuwait: Results of a Survey. *Int. J. Environ. Res. Public Health* **2017**, *14*, 340. [CrossRef]
8. Akashe, M.M.; Uday, V.P.; Ashwin, V.N. Classification of pesticides: A review. *Int. J. Res. Ayurveda Pharm.* **2018**, *9*, 144–152.
9. Kole, R.K.; Roy, K.; Panja, B.N.; Sankarganesh, E.; Mandal, T.; Worede, R.E. Use of pesticides in agriculture and emergence of resistant pests. *Indian J. Anim. Health* **2019**, *58*, 53–70.
10. Yawson, D.O. Pesticide use culture among food crop farmers: Implications for subtle exposure and management in Barbados. *Agriculture* **2022**, *12*, 288. [CrossRef]
11. Maksymiv, I. Pesticides: Benefits and Hazards. *J. Vasyl Stef. Prec. Nat. Univ.* **2015**, *2*, 70–76.
12. Singh, G. Movement of Crop Protection Chemicals in Different Environmental Components. *Int. J. Plant Anim. Environ. Sci.* **2019**, *5*, 206–209. [CrossRef]
13. Sudhanshu, B.N.; Alok, K.; Elango, K.; Sankara, R. Role of pesticide application in environmental degradation and its remediation strategies. *Environ. Degrad. Causes Remediat. Strateg.* **2022**, *1*, 36. [CrossRef]
14. Al-Kazafy, H.S. Synthetic fertilizers, roles and hazards. *Fertil. Technol.* **2015**, *1*, 111–133.
15. Damalas, C.; Eleftherohorinos, I. Pesticide exposure, safety issues and risk assessment indicators. *Int. J. Environ Res Public Health* **2011**, *8*, 1402–1419. [PubMed]
16. Cech, R.; Leisch, F.; Zaller, J.G. Pesticide use and associated greenhouse gas emissions in sugar beet, apples, and viticulture in Austria from 2000 to 2019. *Agriculture* **2022**, *12*, 879. [CrossRef]
17. Wandiga, O.S. Use and distribution of organochlorine pesticides. The future in Africa. *Pure Appl. Chem.* **2001**, *73*, 1147–1155. [CrossRef]
18. Boulanger, P.; Dudu, H.; Ferrari, E.; Alfredo, M.J.; Ramos, M.P. Effectiveness of fertilizer policy reforms to enhance food security in Kenya: A macro-micro simulation analysis. *Appl. Econ.* **2022**, *54*, 841–861. [CrossRef]
19. Agrochemical Association of Kenya. *Annual Report*; Agrochemical Association of Kenya: Nairobi, Kenya, 2018; pp. 20–22.
20. FAO. *Practical Guidelines on Pesticides Risk Reduction for Locust Control in Caucasus and Central Asia*; FAO: Rome, Italy, 2019; pp. 1–10.
21. Abdou, K.; Hend, M. Epidemiology of Pesticides in Developing Countries. *Adv. Clin. Toxicol.* **2018**, *3*, 000128.
22. Zheng, S.; Chen, B.; Qiu, X.; Chen, M.; Ma, Z.; Yu, X. Distribution and risk assessment of 82 pesticides in Jiulong River and estuary. *Chemosphere* **2016**, *144*, 1177–1192. [CrossRef]
23. Njoroge, S.; Munyao, T.M.; Odipo, O. Modeling Relationship between Organic Carbon Partition Coefficient and pesticides solubility of pesticides used along the shore of Lake Naivasha, Kenya. *Am. J. Environ. Eng.* **2016**, *6*, 33–37.
24. Varghese, P.; Timothy, B.E. Pesticide poisoning among children in India: The need for an urgent solution. *Glob. Pediatr. Health* **2022**, *9*, 1–7. [CrossRef]
25. Kaur, R.; Mavi, G.K.; Raghay, S. Pesticides Classification and its Impact on Environment. *Int. J. Curr. Microbiol. Appl. Sci.* **2019**, *8*, 1889–1897. [CrossRef]
26. Silva-Madera, R.J.; Joel, S.; Aarón, A.P.; Mendoza, J.; Hazael, R.C.; Daniel, R.; Mireya, Z.R.; Erandis, D.S. Pesticide Contamination in Drinking and Surface Water in the Cienega, Jalisco, Mexico. *Water Air Soil Pollut.* **2021**, *232*, 43. [CrossRef]
27. Menger, F.; Gustaf, B.; Ove, J.; Lutz, A.; Karin, W.; Jenny, K.; Pablo, G. Identification of Pesticide transformation products in surface water using suspect screening combined with national monitoring data. Environ. *Sci. Technol.* **2021**, *55*, 10343–10353. [CrossRef] [PubMed]

28. Phung, D.T.; Des, C.; Greg, M.; Rutherford, S.; Chu, C. Pesticide regulations and farm worker safety: The need to improve pesticide regulations in Viet Nam. *Bull. World Health Organ.* **2012**, *90*, 468–473. [CrossRef] [PubMed]
29. Marete, G.; Lalah, J.O.; Mputhia, J.; Wekesa, V.W. Pesticide usage practices as sources of occupational exposure and health impacts on horticultural farmers in Meru County, Kenya. *Heliyon* **2021**, *7*, e06118. [CrossRef] [PubMed]
30. Eddleston, M.; Hiroshi, N.; Chien-Yu, L.; Mark, L.D.; Shu-Sen, C. Pesticide use, agricultural outputs, and pesticide poisoning deaths in Japan. *Clin. Toxicol.* **2022**, *60*, 933–941. [CrossRef]
31. Lewis, K.A.; Tzilivakis, J.; Warner, D.J.; Green, A. An international database for pesticide risk assessments and management. *Hum. Ecol. Risk Assess.* **2016**, *22*, 1050–1064. [CrossRef]
32. Lalah, J.O.; Omwoma, S.; Osano, F.O.; Omukunda, E.; Wafubwa, G.; Muyekho, D.; Schramm, K.W. Assessment of potential risks and effectiveness of agrochemical usage in a catchment: A case study of the Nzoia Nucleus Estate sugarcane farms in western Kenya. In *Integrated Analytical Approaches for Pesticide Management*; Paperback; Maestroni, B., Cannavan, A., Eds.; Academic Press Publishers, Elsevier: Cambridge, MA, USA, 2018; p. 338.
33. Boedeker, W.; Watts, M.; Clausing, P.; Marquez, E. The global distribution of acute unintentional pesticide poisoning: Estimations based on a systematic review. *BMC Public Health* **2020**, *20*, 1875. [CrossRef]
34. Blakey, D.H.; Marc, L.; Lavigne, J.; Danny, S.; Jean-Marc, P.; Jean-Marc, S.; Biederbick, W.; Regine, H.; Willi, B.; Hisayoshi, K.; et al. A screening tool to prioritize public health risk associated with accidental or deliberate release of chemicals into the atmosphere. *BMC Public Health* **2013**, *13*, 253271.
35. Hoppin, J.A.; John, L.A.; Monty, E.; Marcia, N.; Barry, R. Environmental Exposure Assessment of Pesticides in Farmworker Homes. *Environ. Health Perspect.* **2006**, *114*, 929–935. [CrossRef] [PubMed]
36. Qingwei, B.; Donghong, W.; Zijian, W. Review of screening systems for prioritizing chemical substances. *Crit. Rev. Environ. Sci. Technol.* **2013**, *43*, 1011–1041.
37. Gustafson, D.I. Groundwater ubiquity score: A simple method for assessing pesticide leachability. *Environ. Toxicol. Chem.* **1989**, *8*, 339–357. [CrossRef]
38. Dabrowski, J.; Micael, S.; Justinus, M.; Wepener, V. Prioritizing agricultural pesticides in South Africa based on their environmental mobility and potential human health effects. *Environ. Int.* **2014**, *62*, 31–40. [CrossRef]
39. Harmon, J.O.; Siggins, A.; Healy, M.G.; McGinley, J.; Mellander, P.E.; Morrison, L.; Ryan, P.C. A risk ranking of pesticides in Irish drinking water considering chronic health effects. *Sci. Total Environ.* **2022**, *829*, 154532. [CrossRef]
40. Abong'o, D.A.; Wandiga, S.O.; Jumba, I.O.; Odongomadadi, V.; Henrikkylin, L. Impacts of pesticides on human health and environment in the River Nyando catchment, Kenya. *Int. J. Humanit. Arts Med. Sci.* **2014**, *2*, 1–14.
41. Otieno, P.O.; Okinda, P.O.; Lalah, J.O.; Pfister, G.; Schramm, K.W. Monitoring the occurrence and distribution of selected organophosphates and carbamate pesticide residues in the ecosystem of Lake Naivasha, Kenya. *Toxicol. Environ. Chem.* **2014**, *97*, 51–61. [CrossRef]
42. Mutai, C.; Inonda, R.; Njage, E.; Ngeranwa, J. Determination of Pesticide Residues in Locally Consumed Vegetables in Kenya. *Afr. J. Pharmacol. Ther.* **2015**, *4*, 1–6.
43. Macharia, I. Pesticides and Health in Vegetable Production in Kenya. *BioMed Res. Int.* **2015**, *24*, 15–16. [CrossRef]
44. Swati, S.; Dawa, B.; Sanjib, S.; Benoy, K.; Rai, J.P.; Soumen, H.; Min, B. Analyses of pesticide residues in water, sediment and fish tissue from river Deomoni flowing through the tea gardens of Terai Region of West Bengal, India. *Int. J. Fish. Aquat. Sci.* **2015**, *3*, 17–23.
45. Momanyi, V.N.; Keraka, M.; Abong'o, D.A.; Warutere, P.N. Types and Classification of Pesticides Used on Tomatoes Grown in Mwea Irrigation Scheme Kirinyaga County, Kenya. *Eur. J. Nutr. Food Saf.* **2019**, *11*, 83–97.
46. Omwenga, I.; Kanja, L.; Zoomer, P.; Louisse, J.; Ivonne, M.C.; Mol, H. Organophosphate and carbamate pesticide residues and accompanying risks in commonly consumed vegetables in Kenya. *Food Addit. Contam: Part B* **2021**, *14*, 48–58.
47. KEPHIS. *Annual Report and Financial Statements for the Year Ended 30th June 2017*; KEPHIS: Nairobi, Kenya, 2017; pp. 12–14.
48. Government of Kenya. *7th Annual Report on Progress Made in Fulfilling the International Obligations of the Republic of Kenya*; Government Printer: Nairobi, Kenya; pp. 194–195.
49. Sarkar, S.; Bernardes, J.; Kelly, J.; Niklas, M.; Kees, J. *The Use of Pesticides in Developing Countries and Their Impact on Health and Right to Food*; Directorate General for External Policies; Policy Department: Brussels, Belgium, 2021; pp. 1–3.
50. Shete, A.; Shete, A.A.; Dube, S.P.; Dubewar, A.P. Sample size calculation in bio statistics with special reference to unknown population. *Int. J. Innov. Res. Multidiscip. Field* **2020**, *6*, 236–238.
51. Abbasi, A.; Ayesha, S.; Namra, H.; Sammia, R.; Zujaja-tul, M.; Gul, S.; Ashraf, M.; Alvina, G.K. Agricultural Pollution: An Emerging Issue. In *Improvement of Crops in the Era of Climatic Changes*; Ahmad, P., Ed.; Springer: New York, NY, USA, 2014; Volume 1, pp. 347–388.
52. Government of Kenya. *Trans Nzoia County Integrated Development Plan 2018–2022 Indicator Handbook*; Government Printer: Nairobi, Kenya, 2018; pp. 1–13.
53. Adusumilli, N.C.; Ronald, D.L.; Edward, R.; Joshua, D.W.; Allen, W.S. Effect of Agricultural Activity on River Water Quality: A Case Study for the Lower Colorado River Basin. In Proceedings of the Southern Agricultural Economics Association Annual Meeting, Corpus Christi, TX, USA, 5–8 February 2011.
54. Rohila, K.; Ansul, D.; Maan, A.K.; Krishan, K. Impact of Agricultural practices on Environment. *Asian J. Microbiol. Biotechnol. Environ. Sci.* **2017**, *19*, 145–148.

55. Zajícová, K.; Chuman, T. Effect of land use on soil chemical properties after 190 years of forest to agricultural land conversion. *Soil Water Res.* **2019**, *14*, 121–131. [CrossRef]
56. Gunawardhana, W.D.T.M.; Jayawardhana, J.M.C.K.; Udayakumara, E.P.N. Impacts of agricultural practices on water quality in Uma Oya catchment area in Sri Lanka. *Procedia Food Sci.* **2015**, *6*, 339–343. [CrossRef]
57. Arunrat, N.; Serenonchani, S.; Wang, C. Carbon footprint and predicting the impact of climate change on carbon sequestration ecosystem services of organic rice farming and conventional rice farming: A case study in Phichit Province, Thailand. *J. Environ. Manag.* **2021**, *289*, 112458. [CrossRef] [PubMed]
58. Uzoh, I.; Igwe, C.; Okebalama, C.B.; Olubukola, O.B. Legume-maize rotation effect on maize productivity and soil fertility parameters under selected agronomic practices in a sandy loam soil. *Sci. Rep.* **2019**, *9*, 8539. [CrossRef]
59. Yu, H.; Wang, F.; Shao, M.; Huang, L.; Xie, Y.; Xu, Y.; Kong, L. Effects of Rotations with legume on soil functional microbial communities involved in phosphorus transformation. *Front. Microbiol.* **2021**, *12*, 661100. [CrossRef]
60. Bullock, D.G. Crop rotation. *Cric. Rev. Plant Sci.* **1992**, *11*, 309–326. [CrossRef]
61. Deen, W.; Martin, R.; Hooker, D.; Gaudin, A. Crop rotation trends: Past, present and future benefits and drivers. In *Crop Rotations: Farming Practices, Monitoring and Environmental Benefits*; Nova Science Publications: New York, NY, USA, 2016.
62. Nielson, D.C.; Calderon, F.J. Fallow Effects on Soil. In *Soil Management: Building a Stable Base for Agriculture*; Jerry, L.H., Thomas, J.S., Eds.; USDA-ARS: New York, NY, USA, 2011; pp. 287–290.
63. Hasanuzzaman, M.; Rahman, M.A.; Islam, M.S.; Salam, M.A.; Nabim, R. Pesticide residues analysis in water samples of Nagarpur and Saturia Upazila, Bangladesh. *Appl. Water Sci.* **2018**, *8*, 8. [CrossRef]
64. Aziz, I.; Ashraf, M.; Islam, K.R. Crop rotation impact on soil quality. *Pak. J. Bot.* **2011**, *43*, 949–960.
65. Piekut, A.; Renata, B.; Ewa, M.; Małgorzata, Ć.; Ilona, H.; Grzegorz, D.; Elżbieta, G. Is the soil quality monitoring an effective tool in consumers'mprotection of agricultural crops from cadmium soilmcontamination?—A case of the Silesia region (Poland). *Environ. Monit. Assess* **2018**, *190*, 25–34. [CrossRef]
66. Shangman, H.; Na, Z.; Lim, T.; Xiao, J.; Unyang, L. Effects of soil PH and organic matter content on nutrient availability in maize, Zea mays L., rhizospheric soils of non-ferrous smelting area. *Environ. Monit. Assess.* **2019**, *191*, 634.
67. Kicinska, A.; Radosław, P.; Miguel, I. Changes in soil pH and mobility of heavy metals in contaminated soils. *Eur. J. Soil Sci.* **2022**, *73*, e13203. [CrossRef]
68. Arunrat, N.; Sansupa, C.; Kongsurakan, P.; Sereenonchai, S.; Hatano, R. Soil microbial diversity and community composition in rice–fish co-culture and rice monoculture farming system. *Biology* **2022**, *11*, 1242. [CrossRef]
69. Zheng, Z.; Changbin, C.; Deping, Z.; Qingfeng, W.; Shuhang, W.; Xianqing, Z.; Ke, S.; Weiguang, L. Soil bacterial community composition in rice–fish integrated farming systems with different planting years. *Sci. Rep.* **2021**, *11*, 10855.
70. Muendo, B.M.; Shikuku, V.S.; Getenga, Z.M.; Lalah, J.O.; Wandiga, S.O.; Muriira, K.G.; Rothballer, M. Enhanced hexazinone degradation by a *Bacillus species* and *Staphylococcus species* isolated from pineapple and sugarcane cultivated soils in Kenya. *Environ. Chem. Ecotoxicl.* **2022**, *4*, 106–112.
71. Afolabi, T.; Morakinyo, O.B.; Adeboye, O.T. Environmental Effects of Application of Fertilizers and Pesticides on Water and Soil in Ibadan, Nigeria. *J. Emerg. Trends Eng. Appl. Sci.* **2013**, *4*, 773–777.
72. Yanjun, S.; Huimin, L.; Dawen, Y.; Shinjiro, K. Effects of agricultural activities on nitrate contamination of groundwater in a Yellow River irrigated region. In Proceedings of the Water Quality: Current Trends and Expected Climate Change Impacts, Melbourne, Australia, 28 June–7 July 2011.
73. Tang, C.; Chen, J.; Shindo, S.; Sakura, Y.; Zhang, W.; Shen, Y. Assessment of groundwater contamination by nitrates associated with wastewater irrigation: A case study in Shijiazhuang region, China. *Hydrol. Processes* **2004**, *18*, 2303–2312.
74. Anitha, P.; Sylvester, L.; Lyantagaye, G.N. A Review of Agricultural Pesticides Use and the Selection for Resistance to Insecticides in Malaria Vectors. *Adv. Entomol.* **2014**, *2*, 120–128.
75. Démares, F.J.; Schmehl, D.; Bloomquist, J.R.; Cabrera, A.R.; Huang, Z.Y.; Lau, P.; Rangel, J.; Sullivan, J.; Xie, X.; Ellis, J.D. Honey Bee (*Apis mellifera*) Exposure to Pesticide Residues in Nectar and Pollen in Urban and Suburban Environments from Four Regions of the United States. *Environ. Toxicol. Chem.* **2022**, *41*, 991–1003. [CrossRef]
76. Swati, S.; Dawa, B.; Sanjib, S.; Benoy, K.; Joydeb, P.; Soumen, H.; Min, B. Analysis of pesticide residues in water, sediment and fish tissue from river Deomoni flowing through the tea gardens of Terai Region of West Bengal, India. *Int. J. Fish. Aquat. Stud.* **2015**, *2*, 17–23.
77. Behfar, A.; Zahra, N.; Mahammad, H.; Gholamreza, R.; Mohammad, R.; Nafiseh, S.; Behrooz, J. The organochlorine pesticide levels in Kariun River water. *Jundishapur J. Nat. Pharm. Prod.* **2013**, *8*, 41–46. [CrossRef]
78. Abong'o, D.A.; Wandiga, S.O.; Jumba, I.O.; Van den, B.P.; Nazariwo, B.B.; Madadi, V.O.; Wafula, G.A.; Kylin, H.; Nkedi-Kizza, P. Organochlorine pesticide residue levels in soil from the Nyando River Catchment, Kenya. *Afr. J. Phys. Sci.* **2015**, *2*, 18–32.
79. Nakata, H.; Kawazoe, M.; Arizono, K.; Abe, S.; Kitano, T.; Shimada, H. Organochlorine pesticides and polychlorinated biphenyl residues in foodstuffs and human tissues from china: Status of contamination, historical trend, and human dietary exposure. *Arch. Environ. Contam. Toxicol.* **2002**, *43*, 473–480. [CrossRef]
80. Yarpuz-Bozdogan, N. The importance of personal protective equipment in pesticide applications in agriculture. *Curr. Opin. Environ. Sci. Health* **2018**, *4*, 1–4. [CrossRef]
81. Mengistie, T.; Belay, A.; Mol, P.P.; Oosterveer, P. Pesticide use practices among smallholder vegetable farmers in Ethiopian Central Rift Valley. *Environ. Dev. Sustain.* **2017**, *19*, 301–324.

82. Nerozzi, C.; Sandra, R.; Giovanna, G.; Diego, B.; Marcella, S.; Marc, Y. Effects of Roundup and its main component, glyphosate, upon mammalian sperm function and survival. *Sci. Rep.* **2020**, *10*, 11026. [CrossRef]
83. Kwiatkowska, M.; Huras, B.; Bukowska, B. The effect of metabolites and impurities of glyphosate on human erythrocytes (in vitro). *Pestic Biochem. Phys.* **2014**, *109*, 34–43.