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HERBICIDE USE IN NIGERIA: A REVIEW OF ITS EFFECTS ON HUMAN, ANIMAL AND ENVIRONMENTAL HEALTH

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ABSTRACT. Herbicides are a class of pesticide compounds with a specific role in weed control. Most herbicides have a positive effect on crop production; however, they are also harmful to the environment, animals, and humans when misused. The aims of this study were to identify commonly used herbicides in Nigeria, examine the effects of herbicides from the perspective of One Health (i.e., the health of humans, animals, and the environment), and increase public awareness of the negative impact of herbicide misuse on human, animal, and environmental health in Nigeria. We conducted a systematic literature search for this study using Google Scholar, the Bielefeld Academic Search Engine (BASE), Research Gate, and PubMed, focusing on research studies conducted in Nigeria. In total, 192 articles were included in this review. Atrazine, glyphosate, metolachlor, paraquat, and 2,4-D are the most commonly used herbicides in Nigeria. According to reports, some of these chemicals inhibit plant photosynthesis and disrupt the female luteinising hormone surge, which disrupts ovulation. Moreover, these chemicals can lead to negative outcomes, such as headaches, oxidative stress, and pollution. Only 1.0, 9.4, and 16.1% of the studies examined the impact of herbicides on human, animal, and environmental health, respectively. Similarly, only 11 studies (5.7%) investigated bioherbicide development in Nigeria, and only 2.6% tested for herbicide residues in crops. Nigeria desperately needs public education regarding the use of herbicides. One health intervention is urgently needed.

Keywords: herbicides; one health; public health; weeds.

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INTRODUCTION

A significant part of every economy is agriculture, and Nigeria is no exception, accounting for about 21.91% of the country's GDP (Plecher, 2020; Singh-Peterson and Iranacolaivalu, 2018). For most Nigerians, farming and other agricultural pursuits are the main sources of sustained income (Ibiremo *et al*., 2011). A variety of issues may contribute to the low production of farmers' fields, but inadequate weed control typically ranks as one of the main causes. In the tropics, controlling weeds is never simple (Ekeleme *et al*., 2021). As a substantial contributor to biodiversity in agricultural systems worldwide, weeds constitute one of the main biotic barriers to effective crop production in sub-Saharan Africa (SSA) (Gerasimova and Mitova, 2020). Weeds compete with crop plants for light, nutrients, and moisture, and this creates stress factors for crops, thereby leading to significant yield loss (Qasem and Foy, 2008) in many cropping systems. Several weed species also act as alternative hosts for pests, insects, and diseases (Kumar *et al*., 2021). Farmers devote more time and resources to controlling weeds, and the financial burden of managing weeds is greater than the total cost of managing other pests (Chikoye *et al*., 2000).

The expense of managing weeds accounts for roughly 75% of the total cost of pest control in crop fields (Samedani *et al*., 2013). The most common approach to weeding in smallholder farms is hand weeding. Depending on the weed species and the weed pressure, smallholder farmers carry out hand weeding three or four times in a cropping cycle. Perennial weeds, such as *Imperata cylindrica* (L.) and *Panicum maximum* (Jacq.), predominate, making hoe weeding necessary. Hand weeding is a tedious activity that either delays work or takes longer to complete (Gianessi, 2010). Chemical weed control is an alternative to manual weeding because it is quicker, requires less labour, and provides better control, although it depends on many factors, including the weed type, density, and environment as well as the herbicide formulation and mode of action (Gianessi, 2010; Teasdale and Cavigelli, 2010).

Herbicides are estimated to make up over 72% of all pesticides used to eradicate pests in agricultural fields (Samedani *et al*., 2013). Herbicide usage (HU) among smallholder and medium-sized farmers in West Africa has risen due to rising costs and a general lack of labour for hand weeding (Akobundu, 1980; Howeler, 2013). Among the benefits of herbicides is the reduction of manual weeding, which is labour intensive, physically strenuous, and often harmful to the farmer's health and well-being (Gianessi, 2010). Herbicide use allows farmers to spend more time expanding their farming area, developing kitchen gardens, and engaging in off-farm activities (Gianessi, 2010). Women and children who often shoulder a significant portion of the weeding workload may have greater availability for childcare and educational pursuits, respectively (Tamru *et al*., 2017). Farmers can obtain more crops from their land using herbicides. These chemicals also make it easier for farmers to switch to conservation agriculture, which reduces soil erosion and carbon loss (Haggblade *et al*., 2017).

However, herbicides also negatively impact plant and soil environments (Ghazi *et al*., 2023). The increasing evolution of herbicide-resistant weed biotypes in different cropping systems remains a concern (Kremer, 2005). Large amounts of herbicide residues often aggregate in the topsoil layer where microbial activity takes place (Amal *et al*., 2003; Gong *et al*., 2001; Osman *et al*., 2005). Herbicide and pesticide residues contaminate soils and water, remain in crops, make their way up the food chain, and ultimately end up in human diets and water (Taylor *et al*., 2003). The worldwide use of phenylurea herbicides (PUHs) has led to their discovery in food products and various environmental compartments (Lu *et al*., 2018; Wang *et al*., 2015). For instance, reports suggest that PUHs harm people, small mammals, and aquatic species (Blondel *et al*., 2013; Lu *et al*., 2018). It has been suggested that isoproturon, diuron, and linuron may have cytogenetic, mutagenic, carcinogenic, endocrine-disrupting, and teratogenic effects on both humans and animals (Lu *et al*., 2018; Orton *et al*., 2009). Consequently, we must employ innovative techniques to mitigate the detrimental impacts of these substances on human, animal, and environmental health. One potential approach is the One Health framework, which acknowledges the interconnectedness and interdependence of human health and the health of domestic and wild animals, plants, and the broader environment, including ecosystems (Olagunju *et al*., 2023; WHO, 2021). Adsorbents, including peat fibre, clay, bottom ash, fly ash, and zeolite, can effectively extract herbicides from soil (Ghazi *et al*., 2023). Furthermore, we can implement One Health strategies by employing natural extracts from *Nerium* and olive for weed management (Al-Samarai *et al*., 2018) and by instructing farmers on the detrimental impacts of excessive herbicide use and appropriate application.

In recent years, Nigeria has seen a notable increase in the use of herbicides for weed control (Abakpa *et al*., 2024). The ease of application, efficacy in controlling common weeds in Nigerian farms, and the growing challenge of finding workers to perform the labour-intensive manual weed cutting process have all contributed to this increase (Tijani, 2006). There are no published data on the use of herbicides in agriculture or other activities in Nigeria. However, the quantity of herbicides used in Nigeria increased from 24,935.78 metric tonnes (Mt) to 175,975.49 MT from 2010 to 2020, with a total of 548,327,000,000 MT used during the period based on the Usman (2021) report with data obtained from the National Bureau of Statistics (NBS) Abuja in February 2021 on pesticide imports into Nigeria. Hence, the objectives of our study are to: determine the most used herbicide(s) in Nigeria; study the effect of herbicides through the One Health lens (i.e., human, animal, and environmental health); study the effect of herbicides on agricultural production; and raise awareness of the impacts the use of these chemicals has on living organisms and their non-living environment in Nigeria. To the best of our knowledge, this is the first paper to study the trend of HU in Nigeria.

MATERIALS AND METHODS

Information sources and search strategy

Publications indexed in Google Scholar, Bielefeld Academic Search Engine (BASE), Research Gate, and PubMed were examined. There were no restrictions on the year of publication, and only research papers were reviewed.

The search approach entailed choosing suitable terms and phrases pertaining to studies and researches where herbicides application was the focus and were carried out in Nigeria. We employed the search phrases in combination with Boolean operators (AND, OR, and NOT) to efficiently retrieve pertinent material. The search construction used was: ("herbicides" OR "atrazine" OR "glyphosate" OR "paraquat" OR “2,4-D” OR “metolachlor” OR “propanil” OR “pendimethalin”) AND ("human" OR "animal" OR "environment" OR "water" OR "soil" OR "microbes" OR "crop") AND (“Abia” OR “Adamawa” OR "Akwa Ibom" OR "Anambra" OR "Bauchi" OR "Bayelsa" OR "Benue" OR "Borno" OR "Cross River" OR "Delta" OR "Ebonyi" OR "Edo" OR “Ekiti” OR “Enugu” OR “Federal Capital Territory (FCT)” OR “Gombe” OR “Imo” OR “Jigawa” OR “Kaduna” OR “Kano” OR “Katsina” OR “Kebbi” OR “Kogi” OR “Kwara” OR “Lagos” OR “Nasarawa” OR “Niger” OR “Ogun” OR “Ondo” OR “Osun” OR “Oyo” OR “Plateau” OR “Rivers” OR “Sokoto” OR “Taraba” OR “Yobe” OR “Zamfara”) AND (“State” OR “Nigeria”).

Inclusion and exclusion criteria

We formulated the inclusion criteria to select relevant peer-reviewed studies that provided significant insights into the relationship between herbicides, crop yield, weed management, and human, animal, and environmental well-being. We strictly adhered to our objectives, focusing on published original papers that were indexed in the aforementioned databases and carried out the following research and study objectives in Nigeria: evaluation of the impact of herbicides on microbiological activity in a specific area; determination of the economic feasibility of various herbicides assessed for weed management in agricultural production; evaluation of herbicide efficacy of herbicides and establishment of the optimal rate for achieving maximum crop yields in Nigeria; research on the impact of single- and tank-mix weed control on crop productivity; analysis of herbicide residues in specific areas; assessment of the long-term effects of HU on farmlands, considering the metal content and the associated groundwater risk assessment; exploration of how herbicides affect the survival and mobility of non-target organisms; evaluation of how frequent herbicide use for weed control around homes affects the physical and chemical properties of the soil in specific communities; tracking of the persistence of the herbicides in Fadama and upland soil to pinpoint the soil conditions that encourage herbicide degradation or persistence; and assessment of the efficacy of these herbicides in weed control.

The following types of studies were not included: those that were cited but no full records were found; those that did not have data directly related to the goals of this paper; those that were purely theoretical and did not have any empirical data; those that only looked at the science behind the different types of weeds in Nigerian cropping systems; those that tested how imazapyr seed coating affected weed control; and those that were done outside of Nigeria.

Data analysis

Microsoft Excel 2013 was used for statistical analysis and visualisation.

RESULTS

At the end of this search, 192 studies fit the criteria. Approximately 13.4% of the studies conducted surveys on herbicides in rural areas of Nigeria. Of the studies, 51.6% used herbicides to control weeds around a crop or in an environment. However, only 5 studies, representing 2.6% of the studies, tested the herbicide concentration in crops.

The number of studies conducted on residues in the environment was 16.1%, comprising 31 papers. Surveys of herbicides' effects on human and animal health comprised 1.0 and 9.4% of the papers, respectively. There were only 11 bio-herbicide papers, accounting for 5.7% of the total. These low percentages validate the necessity of conducting this review study.

Herbicides used

Atrazine was the most applied herbicide across studies and was applied in 53 studies, followed by glyphosate, which it was applied in 40 studies. These were followed by metalochlor (38 studies), paraquat (36 studies), 2,4-D (19 studies), pendimenthalin (16 studies), propanil (10 studies), alachlor (10 studies), and nicosulfuron (9 studies, respectively), and imadazoline herbicides; imazapyr and imazaquin were employed in 6 studies. These herbicides were either applied alone or in combination with other herbicides (*Figure 1*).

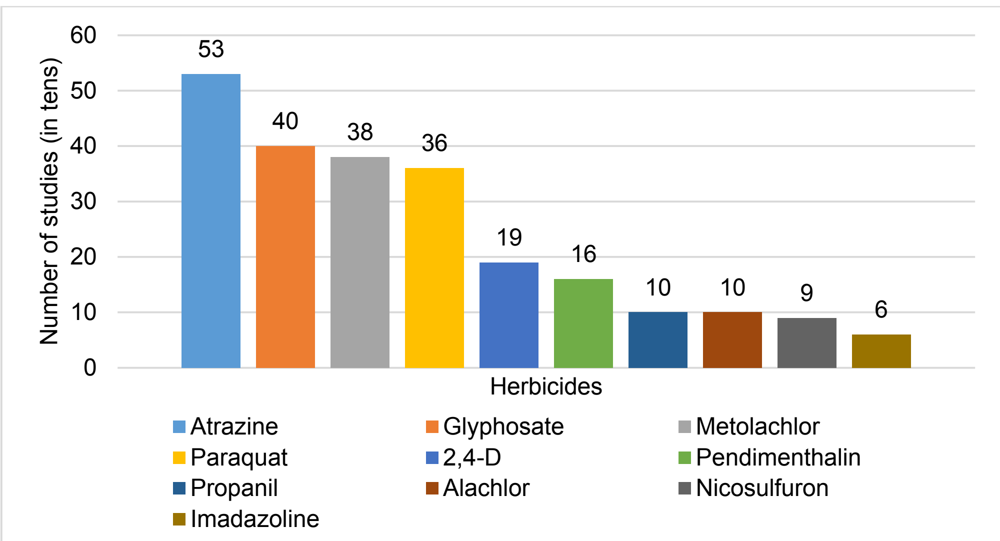

Figure 1 – Herbicides commonly used in Nigeria and the number of studies in which the following herbicides were used: atrazine, glyphosate, metolachlor, paraquat, 2,4-D, pendimenthalin, propanil, alachlor, nicosulfron, and imadazoline

Study regions

The state in which the highest number of studies were conducted was Oyo State (27 studies), followed by Ogun, Kaduna, Kwara, and Benue States, with 16, 14, 12, and 10 studies, respectively.

However, no studies were recorded in 7 states: Akwa Ibom, Bayelsa, Imo, Kebbi, Taraba, Yobe, and Zamfara States (*Figure 2*).

Survey of herbicide use

According to surveys (*Table 1*) carried out in Abia, Benue, Enugu, Ogun, Oyo, and Rivers States by Iyagba (2013) and Udensi *et al*. (2020), most farmers and other end users had been exposed to herbicides during their application. Many exposed individuals indicated that they had not used personal protective equipment or other protective measures as recommended (Joseph *et al*., 2020; Olughu *et al*., 2019;). The majority of those exposed saw no doctors. This illustrates the typical behaviour of ordinary Nigerians in rural areas, who often postpone consultations until health issues escalate.

Alkali *et al*. (2021) showed that weeds were the biggest problem for farming in the study area, which included Bolori, Bulumkutu, Gamboru custom, Gwange, Mairi, the University of Maiduguri campus, and Wulari. Because of this, farmers used herbicides more often than other types of pesticides (Abakpa *et al*., 2024; Adejori and Akinnagbe, 2022; Adekunle *et al*., 2017; Agahiu and Akogu, 2019; Babatunde *et al*., 2019; Bauchi *et al*., 2009; Eifediyi *et al*., 2014; Olayinka *et al*., 2019; Oluwole and Cheke, 2009; Olughu *et al*., 2019; Yakubu *et al*., 2010). These results agree with FAOSTAT (2018) reports, which show that, among the several pesticide groups, herbicides are the most commonly utilised (49%).

Tologbonse and Adekunle (2000) mentioned that rural farmers from Benue could not afford herbicides due to the high cost and scarcity of preferred products. As indicated by Fadipe *et al*. (2014), more farmers (88%) are willing to spend more if they can access agrochemicals and fertilisers nearby. However, these choices are influenced by various socioeconomic factors, such as crop production, farming experience, understanding the mode of action of herbicides, education, and farmers' income. Kughur (2012) revealed that farmers applying herbicides experienced symptoms, such as fatigue, nausea, vertigo, and ocular and dermatological illnesses. However, Kughur's assessment suggests that farmers' efforts to quickly cover large areas of agricultural land and the use of defective spraying equipment could lead to this linkage.

The study did not mention the specific names of the herbicides. Of respondents, 95% reported experiencing health issues as a result of pesticides either during or after their application (Adekunle *et al*., 2017). The symptoms included chest pain, burning sensation, skin redness, white patches, cough, burning, stinging, itchy eyes, dizziness, vomiting, and shortness of breath. Furthermore, Adekunle *et al*. (2017) attributed these prevalent symptoms to exhaustion and weariness following field activity.

Herbicide use for controlling weeds

All studies listed in *Table 2* conducted research on herbicide use to control weeds around crops. In contrast to manual weeding, herbicide use decreased the need for manual labour in crop cultivation, thereby enhancing crop yield and farmers' income (Akadiri *et al*., 2017; Aliyu and Lagoke, 2001; Ugbe *et al*., 2021; Baba *et al*., 2015; Ekeleme *et al*., 2021; Ibrahim and Jimin, 2023; Imeokparia *et al*., 1992; Imoloame, 2020; Lagoke *et al*., 1981; Ogbuji, 2024; Olorukooba *et al*., 2022).

Table 1 – Studies that carried out herbicide surveys and the states or geopolitical zone where the surveys were conducted across Nigeria

Trade name	Active ingredients	State	Zone	References
-	-	Rivers State	South South	Iyagba *et al*., 2013
-	Paraquat	Abia State Benue State Enugu State Ogun State Oyo State Rivers State	South East North Central South East South West South West South South	Udensi *et al*., 2020
-	Atrazine, Paraquat, Chlorbromuron, Metolachlor, Bentazon, Primextra, Dual, Galax, Codal, Oxadiazon, and Glyphosate	Sokoto State	North West	Yakubu *et al*., 2010
Primextra Gold®, Afalon®, Tackle®, and UpRoot 240 EC®	Atrazine, Afalon, Linuron, Metolachlor, glyphosate, Paraquat, 2, 4-D, Chlorsulfuron, and Clethodim	Abia State Benue State Ogun State Oyo State	South East North Central South West South West	Ekeleme *et al*., 2019
Touch Down®, Clear Weed®, Round Up® and Everest®	Glyphosate and flucarbazone-sodium	Ondo State	South West	Adejori and Akinnagbe, 2022
AtraForce®, Gramazone®, Primextra® and Round-Up®	2,4-D, Atrazine, Paraquat, Metolachlor, and Glyphosate	Ekiti State	South West	Oluwole and Cheke, 2009
Primextra®, Gramoxone®, Atraforce®, Amine®, Roundup®	Metolachlor, Paraquat, Atrazine, 2,4-D, Glyphosate	Oyo State	South West	Adekunle *et al*., 2017
-	Diuron, 2,4-Dmine, Paraquat, Glyphosate, Atrazine, Metolachlor and Pendimenthalin	Oyo State	South West	Babarinsa *et al*., 2018

-	Atrazine, Paraquat, Glyphosate, Propanil, Butachlor, Oxidiaxone, 2,4-D-Amine and Pendimenthalin	Plateau State	North Central	Umukoro *et al.*, 2016
Fusilade® and Primextra®	Triazines, Fluazifop-p-βutyl and S-Metolachlor	Kano State	North West	Isah *et al.*, 2020
-	Glyphosate, Paraquat, Atrazine, Alachlor	Edo State	South South	Uddin *et al.*, 2015
Clear Weed®, Touch Down®, Round-Up®, and Everest®	Glyphosate and flucarbazone-sodium	Ondo State	South West	Adejori and Akinnagbe, 2022
Paraforce®, Sarosate®, Force-off®, Fitscosate®, Actraforce®, Dsitop®, and Weed off®	Paraquat, glyphosate and atrazine	Benue State	North Central	Abakpa *et al.*, 2024
Primextra® and Gramazone®	Atrazine and Paraquat	Niger State	North Central	Baba *et al.*, 2015
-	Atrazine and glyphosate	Ekiti State	South West	Agbenin *et al.*, 2018
Pentashi®, Clearweed®, Dragon® (Gramazol) and Slasher®	2-4-D, glyphosate and Paraquat	Adamawa State	North East	Joseph *et al.*, 2020
-	2,4-D, paraquat, butylate, atrazine, bladex, glyphosate	Oyo State	South West	Olatinwo *et al.*, 2022
-	paraquat dichloride and glyphosate	Ondo State Kwara State	South West North Central	Aminu *et al.*, 2020
Gramozone®, Parae force®, Weed crush, Touch down® etc	Paraquat and glyphosate	Oyo State Osun State Ekiti State Ondo State Ogun State Lagos State	South West	Olabode *et al.*, 2011

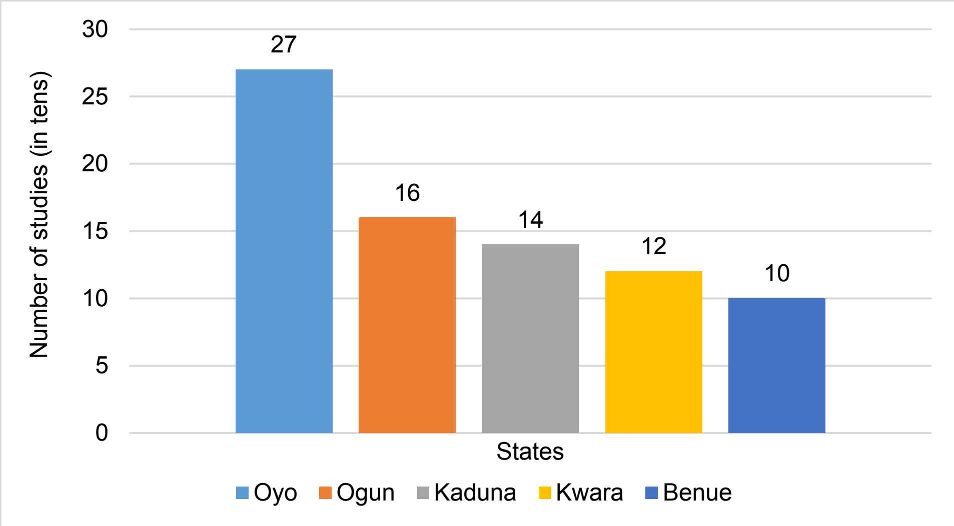

Figure 2 – Trends of herbicide usage in Nigerian states

Omovbude and Udensi (2013) and Shittu and Bassey (2023) found that herbicide use enhanced cowpea productivity, promoting increased growth and yield by alleviating weed infestation. Magani *et al.* (2012) determined that propanil was effective in managing weeds in sesame to enhance its yield. Applying butachlor at a rate of 1.0 kg a.i. ha^{-1} can serve as a viable substitute for hoe weeding, resulting in efficient weed management and an increased sesame yield (Audu *et al.*, 2021). According to Osunleti *et al.* (2022a), weed density and weed species composition decreased, ranging from 88.74 to 96.55% and from 66.92 to 75.53%, respectively, after HU. Unamma and Melifonwu (1986) found that the application of fluometuron, chloramben, diuron/paraquat, simazine, and atrazine/metolachlor at rates of 1.4, 2.7, 1.6, 5.7 and 3.8 kg a.i. ha^{-1}, respectively, effectively managed weeds and significantly increased tuber yields.

Glyphosate application enhances microbial activity in the soil due to its function as an organophosphate, which allows a diverse array of microorganisms to break it down and use it as a carbon, nitrogen, and/or phosphorus food source. Furthermore, glyphosate use increases the soil-accessible nitrogen, leading to improved soil microbial activity. Consequently, it can be considered a superior option for weed management in soil conservation tillage practices, particularly in tropical soils (Adegaye *et al.*, 2023). Ezeri (2002) conducted a study that revealed that glyphosate effectively managed water hyacinths and related weeds without causing any harmful impact on fish and other aquatic biodiversity. Due to its ability to promote the increased growth and yield performance of cocoa, its significantly lower application cost compared to manual weeding, and its ability to maintain a weed-free environment for a longer duration than alternative treatments, cocoa plantations favour glyphosate for weed management (Ayegboyin *et al.*, 2020). Chikoye *et* *al.* (2005) conducted a study that demonstrated glyphosate's highest efficacy in managing cogongrass in the short term. Based on the findings of Take-tsaba *et al.* (2011), the use of glyphosate, pendimethalin, and butachlor had a notable impact on the growth characteristics of sesame. Galex and glyphosate have demonstrated effective weed control in cowpea cultivation (Ugbe *et al.*, 2016).

Abakura *et al.* (2015) found that the use of pre-emergence herbicides for weed management significantly impacted both weed control and the growth/yield index of maize. Omisore *et al.* (2016) investigated several techniques for controlling weeds in cowpea cultivation and showed that the application of a pre-emergence herbicide in conjunction with hoe weeding significantly reduced the weed cover score, significantly increased plant height and branch count, and resulted in a greater number of pods per plant and increased grain yield. Furthermore, herbicide application has led to increased grain production (Lawrence and Dijkman, 1997). Danmaigoro *et al.* (2022) found that applying gramazone as a pre- and post-emergence herbicide on rice plots significantly increased the number of spikelets per panicle, lengthened the panicle, increased the number of effective tillers per hill, increased the number of grains per panicle, and improved grain output. Plots subjected to pre- and post-emergence herbicide treatment exhibited the greatest benefit–cost ratio. Osunleti *et al.* (2022b) demonstrated the application of a pre-emergence herbicide for weed control in mango ginger, leading to time and resource savings as well as an improvement in the benefit–cost ratio. The use of prosulfuron and propanil resulted in the greatest grain production compared to all other herbicide treatments, as reported by Haruna *et al.* (2017). Some of the best pre-emergence herbicides for growing cocoyam are diuron, flumioxazin + pyroxasulfone, and sulfentrazone (Adewumi *et al.*, 2024) because they provide the most benefit for the least amount of cost. Ngonadi *et al.* (2023) found that pre-emergence herbicide was the most effective choice for weed control.

Imoloame and Osunlola (2017) recommended applying pendimethalin at a rate of 1.5 kg a.i. ha^{-1}, along with one supplementary hoe weeding (SHW) or pendimethalin at 2.0 kg a.i. ha^{-1}, to achieve efficient pest control of weeds and to increase cowpea grain yield. For regions in the Northern Guinea Savanna areas of Nigeria where noxious weed biotypes, such as *Rotteboelia cochinchinensis*, *Imperata cylindrica*, *Digitaria ciliaris*, and sedges, often require high herbicide rates for effective weed control and a higher grain yield of sorghum, a maximum rate of 3.0 kg a.i. ha^{-1} of pendimethalin can be recommended. Koroma *et al.* (2021) suggest that metolachlor and pendimethalin have shown efficacy in controlling weeds in groundnut plantations in Yola, Nigeria. Cyprian and Onuba (2019) highly recommended Goal Tender 4F for weed control in cocoyam cultivation in the southeastern region of Nigeria.

Korieocha (2021) found that applying atrazine/metolachlor at a rate of 2.5 kg a.i. ha^{-1} together with hand weeding was a successful approach for controlling weeds. This method guaranteed a decrease in weed infestation and biomass as well as an increase in sweet potato root yield. Deshi *et al.* (2019) found that weed management using a combination of herbicides (atrazine and paraquat) as well as using atrazine alone improved the growth and production of potato crops. Lumax, a combination of mesotrione, S-metolachlor, and atrazine, effectively controlled weeds in maize in Nigeria, with rates ranging from 1.88 to 2.96 kg a.i. ha^{-1} (Chikoye *et al.*, 2009). Imoloame (2017) discovered that using metolachlor + atrazine and pendimethalin + atrazine at doses of 1.0 kg a.i. ha^{-1}, as well as more hand weeding, could be a beneficial alternative to hand weeding for effectively controlling weeds, increasing maize yields, and making more money in Nigeria's Southern Guinea Savanna. Akinola and Salami (2016) found that the use of herbicides, specifically atrazine and paraquat, significantly reduced *Tithonia* density, biomass, and height. Furthermore, their implementation resulted in a notable increase in maize plant height, a higher leaf count, and a larger maize girth. In general, their use led to a significant increase in maize grain production. An atrazine formulation is efficacious for weed management in maize when used at dosages below the acceptable threshold (Chikoye *et al.*, 2006). Gani and Daniel (2023) and Gani and Umar (2023) found that applying atrazine at a rate of 0.80 kg a.i. ha^{-1} and raft at a rate of 0.50 kg a.i. ha^{-1} resulted in the production of long finger millet panicles, heavier panicle weights, and 1000-grain weights.

Chikoye *et al.* (2004) and Olatinwo *et al.* (2022) demonstrated that maize grain yields in treatments exposed to herbicides and velvet bean were comparable and significantly higher than those that were unexposed. Chikoye *et al.* (2007) demonstrated the significant potential of rimsulfuron in selectively controlling both annual and perennial weeds in maize. Tizhe *et al.* (2023) suggested that nicosulfuron and bentazone treatments could be used to improve the overall yield of SAMMAZ 17 and SAMMAZ 37 varieties of maize. The study conducted by Falade *et al.* (2023) revealed that the use of propaben led to the attainment of optimal levels of maize shoot dry matter, decreased weed cover, and increased maize cob production. The use of ninosulfuron on certain commercially available maize cultivars had no negative impact on grain yield (Lum *et al.*, 2004; Lum *et al.*, 2005a, 2005b). The sequential application of herbicides (ParaeForce and AminoForce) at defined time intervals decreased weed resistance and enhanced maize growth and yield (Halliru *et al.*, 2022). Rotating lower herbicide rates on flat seed beds and looking into alternatives to pulling weeds by hand can remove weeds effectively, increase maize grain yield, make a profit, and lower herbicide residue in maize production (Imoloame, 2021). Biochar application in combination with either preemergence herbicide or manual hoe weeding improved maize development and productivity (Adeyemi *et al.*, 2019). According to Eni *et al.* (2021), using prometryne pre-emergence herbicides with either metolachlor or acetochlor and planting maize between jack bean or groundnut trees made the herbicides work better and increased the yield of maize cobs and grains.

Agahiu (2020) revealed that the combination formulations of acifluorfen and bentazon, together with asulam, resulted in a greater soybean yield and yield components compared to their individual formulations. According to Udensi *et al.* (2017), it is financially beneficial to use herbicides on a yam–maize–soybean plantation in the Northern Guinea Savanna agro-ecology. According to Aluko *et al.* (2003) and Anikwe *et al.* (2003), herbicides improve production and control weeds in the derived savanna, which has a beneficial impact on soybean farming.

As reported by Mahmoud *et al.* (2013), oxadiazon application resulted in higher average values of plant height, number of branches per plant, number of bolls per plant, boll yield per plot, and boll yield per hectare. Ishaya *et al.* (2007) found that the fertilisers pretilachlor + dimethametryne at 2.5 kg a.i. ha^{-1}, cinosulfuron at 0.05 kg a.i. ha^{-1}, and piperophos + cinosulfuron at 1.5 kg a.i. ha^{-1} were the best at removing weeds, making crops stronger, taller, and less damaged, and increasing the grain yield of sorghum. The correct spacing and effective application of herbicides influence pepper output, effectively controlling weed growth, and greatly enhancing pepper production (Mustapha *et al.*, 2021). Akpasi *et al.* (2023) reported that paraquat herbicide application resulted in elevated levels of moisture, protein, fat, carbohydrate, ash, and vegetable compounds. Furthermore, the nutritional composition of cowpea grain plots treated with herbicides showed modest improvement (Omovbude *et al.*, 2019). To enhance onion production, oxyflorfen (Ibrahim *et al.*, 2011) and chlorthaldimethyl (Sinha and Lagoke, 1983) were applied at the prescribed dosages.

Emeghara *et al.* (2013) presented a varied assessment of the impact of herbicides on crops. The most effective methods for achieving good weed control and high wheat production were metolachlor + prometryne at 1.25 + 1.25 kg a.i. ha^{-1}, oxadiazon at 1.0 kg a.i. ha^{-1}, and propanil + bentazon at 2.0 + 1.0 kg a.i. ha^{-1}, according to Emeghara *et al.* (2013). However, atrazine and its combinations are phytotoxic to wheat plants. Furthermore, Udensi and Oyeye (2016) found that using lower rates of Primextra led to successful melon establishment, characterised by optimal ground cover and abundant flowering. Nevertheless, Primextra at a rate of 1.98 kg a.i. ha^{-1}, Force Top at 2.0 kg a.i. ha^{-1}, and Raft at 2.0 kg a.i. ha^{-1} provided satisfactory (≥ 70%) weed management but resulted in enduring and irremediable damage to crops. The use of herbicides for weed management at the prescribed dosages resulted in improvements in the growth and yield characteristics of agricultural maize. Ordinioha *et al.* (2017) reported potential persistent negative impacts of the herbicides. Herbicides enhanced cassava yields, but they also had certain negative consequences, such as delayed cassava sprouting and transitory leaf bleaching (Ekeleme *et al.*, 2020). Imeokparia (1994) documented both the beneficial and detrimental impacts of herbicides on rice productivity.

Ricepro application for weed management in rice fields makes rice more vulnerable to infestation and damage from *Orseolia oryzivora* (Mohammed *et al.*, 2022). Obadoni and Remison (2005) showed that herbicide application did not yield financial benefits in rice cultivation. Ndahi (1984) found that crops with a low herbicide dose and one hoe weeding produced the same crop yield as those without weeding but with higher herbicide rates.

However, only five studies (Adah *et al*., 2020; Aikpokpodion *et al*., 2013; Ekhuemelo, 2023; Gushit *et al*., 2013; Mohammed *et al*., 2020) examined the amounts of herbicides in crop samples (*Table 2*). Ekhuemelo (2023) examined the herbicide concentration in cowpea grains. In kola nut samples taken from Ogun, Osun, and Oyo States, Aikpokpodion *et al*. (2013) tested alachlor in crop samples. Gushit *et al*. (2013) revealed that during the period under investigation, root crops and leafy vegetable crop samples that were collected had relatively large concentrations of atrazine and 2,4-dichlorophenoxy acetic acid. Adah *et al*. (2020) found that dichloran, heptachlor epoxide, propyzamide, chlorpyrifos, dizinon, endosulfan II, methoxychlor, and mirex were the chemicals most often found in rice samples from three markets in Makurdi and also detected BHC, Aldrin, Trifluralin, Dieldrin, Endrin P, p-DDT, and atrazine. Mohammed *et al*. (2020) revealed elevated concentrations of herbicide residues in rice samples from Borno State and found documented that the residues examined exceeded the maximum residue limits (MRLs) set by the World Health Organization (WHO) and the acceptable daily intake values (ADIs) set by the Food and Agriculture Organization (FAO, 2024).

Table 2 – Studies in which herbicides were used to control weeds in an environment or around a crop

Trade name	Active ingredients	Crop/ Animal	State	Region	References
Movon 450 SC®, Fierce 75 WG®, Merlin Total 600 SC®, Sencor Plus 517.5 SC®, Primextra Gold 600 SC®, Gardoprim Plus Gold 500 SC, Select Max® + Cobra®, Fusilade® Forte® + Cobra®, MaisTer Power 57.5 OD and Touchdown Forte 500 SL®	diflufenican, flufenacet, flurtamone, flumioxazin, pyroxasulfone, indaziflam, isoxaflutole, indaziflam, metribuzin, s-metolachlor, atrazine, terbuthylazine, clethodim, lactofen, fluazifop-p-butyl, lactofen, foramsulfuron-sodium, iodosulfuron-methyl-sodium, thiencarbazone-methyl,	Cassava	Abia State Benue State Ogun State Oyo State	South East North Central South West South West	Ekeleme *et al*., 2021

	cyprosulfamide, andglyphosate				
-	glyphosate and paraquat	*Axonopus compresus (authority)* and *P. maximum*	Ondo state	South West	Adegaye *et al.*, 2023
Primextra®	atrazine and metolachlor	Broadleaf weed, grasses and sedges	Kwara State	North Central	Takim *et al.*, 2023
-	bispyribac-sodium, cyhalofop-butyl, penoxsulam, pendimenthalin, propanil, and thiobencarb	Rice	Nasarawa state	North Central	Ibrahim and Jimin, 2023
-	imazapyr acid	Witchweed	FCT Borno State Niger State	North Central North East North Central	Chikoye *et al.*, 2020
Primextra®, Aminicome®, Paraforce®, and Guard force®	atrazine, metolachlor, paraquat 2, 4-D, and nicosulfuron	*Zea mays* L.	Kwara State	North Central	Imoloame , 2021
Force Up®, Uproot®, Tackle®, Bush clear®, Dragon® and Paraforce®	glyphosate, paraquat, atrazine, nicosulfuron	Broadleaf, grasses and sedges	Kwara State	North Central	Imoloame *et al.*, 2021
Herbicide-coda l Gold®	Prometryne and metolachlor	*Zea mays*	Ogun State	South West	Adeyemi *et al.*, 2019
-	primextra, 2, 4-D, and nicosulfuron	*Zea mays*	Kwara State	North Central	Imoloame *et al.*, 2020
-	galex and fulisade	*Rottboellia cochinchinensis, Euphobia hirta, Euphobia heterophila Imperata cylindrica, Cyperus difformis, Oryza barthis, Chromolaena odorata, Ageratum conyzoides,*	Kwara State	North Central	Omisore *et al.*, 2016

		Tridax procumbens, and *Cyperus rotundus*			
-	paraquat and fluazifopbutyl	*Glycine max*	Ebonyi State	South East	Anikwe *et al*., 2003
vinash®	Glyphosate	*Macrotermes bellicosus*	Edo State	South South	Ekaye *et al*., 2022
Bullet® and raft®	terbuthylazine, acetochlor and atrazine	*Eleusine coracana*	Kaduna State	North West	Gani and Daniel, 2023
-	Pendimethalin	*Vigna unguiculata*	Kwara State	North Central	Imoloame and Osunlola, 2017
probaben® and super union®	prometryne, metolachlor and acetochlor	Maize, jack bean, and groundnut	Ogun State	South West	Eni *et al*., 2021
	atrazine, metolachlor, terbutryne, prometryne, propanil, 2,4-D and bentazon	*Triticum aestivum*	Kano State	North West	Emeghara *et al*., 2013
-	gramazone, paraquat and propanil	*Oryza sativa*	Jigawa State	North West	Danmaigoro *et al*., 2022
primextra gold®, raft® and force top®	atrazine, metolachlor, terbutylazine, atrazine and pendimethalin	*Citrillus colocynthis*	Rivers State	South South	Udensi and Oyeye, 2016
round up®	Glyphosate	*Zea mays*	Rivers State	South South	Ordinioha *et al*., 2017
-	paraquat and atrazine	*Zea mays*	Ekiti State Ondo State	South West South West	Akinola and Salami, 2016
-	fluazifop and propanil	*Sesamum indicum*	Benue State	North Central	Magani *et al*., 2012
codal gold®, galex®, pendilin®	prometryne, metolachlor, pendimethalin and metobromuron	*Vigna unguiculata*	Edo State	South South	Omovbude and Udensi, 2013
-	oxyfluorfen	Broadleaf, grasses, and sedges	Ogun State	South West	Osunleti *et al*., 2022a

-	oxyfluorfen	*Curcuma amada*	Ogun State	South West	Osunleti *et al.*, 2022b
-	pendimethalin	*Sorghum bicolor*	Adamawa State Gombe State	North East North East	Dantata and Shittu, 2014
-	imazaquin and nicosulfuron	*Striga hermonthica*	Oyo State	South West	Ahonsi *et al.*, 2004
-	diuron, atrazine and metolachlor	*Ipomoea batatas*	Abia State Benue State	South East North Central	Korieocha, 2021
round-up®	Glyphosate	Water Hyacinth	Ogun State	South West	Ezeri, 2002
-	alachlor, atrazine and simazine	Cowpea	Benue State Nasarawa State Kogi State Kwara State Niger State Plateau State FCT	North Central North Central North Central North Central North Central North Central North Central	Ekhuemelo, 2023
-	butachlor, glyphosate and pendimethalin	*Sesamum indicum*	Sokoto State	North West	Take-tsaba *et al.*, 2011
	metolachlor, metobromuron, metribuzin, chlorbromuron, deflufenican, diphenamid, linuron and pendimethalin	*Sohum aefhiopicum*	Kaduna State	North West	Aliyu and Lagoke, 1995
-	alachlor, butachlor, chloramben, diuron, paraquat, fluometuron, atrazine, linuron, metolachlor and simazine	*Dioscorea* spp,	Abia State	South East	Unamma and Melifonwu, 1986

	metolachlor and atrazine	*Zea mays*	Kaduna State	North West	Chikoye *et al.*, 2004
-	Glyphosate	*Imperata cylindrica*	Oyo State	South West	Chikoye *et al.*, 2005
-	rimsulfuron	Cogongrass and guineagrass	Oyo State	South West	Chikoye *et al.*, 2007a
lumax®, primextra gold[tm], gesaprim® and rhonazine®	atrazine, metolachlor and mesotrione	*Zea mays*	Oyo State	South West	Chikoye *et al.*, 2009
-	atrazine and paraquat	*Solanum Tuberosum*	Plateau State	North Central	Deshi *et al.*, 2019
challenge 600 sc[a],,lagon 575 sc[a], bullet 700 sc, metric 293 zc[b], stallion cs[b], vigon 420 sc[a], movon 450 sc[a], liberator forte 360 sc[a], wing-p 462.5 ecc, fierce 75 wg, sencor plus 517.5 sc[a], merlin total 600 sc[a], merlin 75 wg[a], merlin flexx 480 sc[a], sencor 480 sc[a], callisto 480 sc[e], goal 4fd, codal gold 412.5 dc[e], primextra gold 660sc[e], authority 480 sc[b], gardoprim plus gold 500 sce	aclonifen, isoxaflutole, acetochlor, atrazine, terbuthylazine, clomazone, metribuzin, pendimethalin, diflufenican, flufenacet, flurtamone, dimethenamid-p, flumioxazin, pyroxasulfone, indaziflam, metribuzin, isoxaflutole, cyprosulfamide, mesotrione, oxyfluorfen, prometryn + s-metolachlor, sulfentrazone and terbuthylazine	Cassava	Abia State Benue State Ogun State Oyo State	South East North Central South West South West	Ekelemi *et al.*, 2020
-	metolachlor, atrazine and pendimethlin	*Zea mays*	Kwara State	North Central	Imoloame, 2017
-	propaben and superunion	*Zea mays*	Ogun State	South West	Falade *et al.*, 2023
-	acifluorfen and bentazon	*Glycine max*	Kogi State	North Central	Agahiu, 2020

-	alachlor, metolachlor, diuron and oxadiazon	*Gossypium* spp	Kaduna State	North West	Mahmoud *et al*., 2013
-	piperophos, oxadiazon, molinate, ruorodifen, bentazone and propanil	*Oryza sativa*	Niger State	North Central	Imeokpari a, 1994
ronstar 250ec®, setoff 20wg®, rilof s 145 g/l®, setoff 63wg 2.5 rifit extra 500ec®, fernoxone 80sp® basagran 450ec® and pipset 35wp®	cinosulfuron, piperophos, propanil, prosulfuron, pretilachlor, 2,4-D and bentazon	*Sorghum bicolour*	Kaduna State	North West	Ishaya *et al*., 2007
-	pendimethalin, pyrithiobac sodium and haloxyfop	*Capsicum annum*	Adamawa State	North East	Mustapha *et al*., 2021
-	Imazaquin	*Striga gesnerioides*	Kano State	North West	Lado *et al*., 2018
-	nicosulfuron	*Imperata cylindrica*	Oyo State	South West	Lum *et al*., 2004
-	nicosulfuron	*Imperata cylindrica*	Oyo State Kwara State	South West North Central	Lum *et al.,* 2005a
-	nicosulfuron	*Imperata cylindrica*	Oyo State Kwara State	South West North Central	Lum *et al*., 2005b
-	atrazine and nicosulphuron	*Zea mays*	Anambra State	South East	Ngonadi *et al*., 2023
-	trifluralin and luometuron	Cotton	Kaduna State	North West	Ogborn, 1969
-	metolachlor and atrazine	Cassava	Ogun State Oyo State	South West South West	Onasanya *et al*., 2021
-	atrazine	Maize	Oyo State	South West	Chikoye *et al*., 2006

-	Glyphosate	*Imperata cylindrica*	Cross River State Benue State Kogi State	South South North Central North Central	Chikoye *et al*., 2007b
Paraeforce® and Aminforce®	paraquat and 2, 4–D amine sl	*Zea mays*	Katsina State	North West	Halliru *et al*., 2022
	Diquat	*Pistia stratiotes*	Kaduna State	North West	Service, 1962
Paraeforce®	Paraquat	*Telfairia occidentalis*	Delta State	South South	Akpasi *et al*., 2023
coda gold®, galex® and pendilin®	-	*Vigna unguiculata*	Edo state	South South	Omovbude *et al.*, 2019
-	glyphosate and paraquat	*Theobroma cacao*	Cross River State	South South	Ayegboyin *et al*., 2020
Primextra gold®, Galex®, Cotoran multi®, Fusilade® and Dual gold®	atrazine, s-metolachlor, metobromuron, fluometuron and fluazifop-p-butyl	Cassava	Kogi State	North Central	Agahiu *et al.,* 2012
-	alachlor, chlordane and endosulfan	Kola nut	Ogun State Osun State Oyo State	South West	Aikpokpodion *et al*., 2013
-	atrazine, diuron, galex, glyphosate and primextra	*Vigna Uniguiculata*	Cross River State	South South	Ugbe *et al*., 2016
-	s matolachlor, pendimenthaline and oxyflourfen	*Allium cepa*	Oyo State	South West	Ibrahim *et al*., 2011
-	atrazine and 2,4-dichlorophenoxy acid	Root and vegetable crops	Plateau State	North Central	Gushit *et al*., 2013
-	s-metolachlor, pendimenthaline and butalachlor	Cowpea	Kaduna State	North West	Ibrahim, 2013
-	Ametryn	Sugarcane	Kwara State	North Central	Takim *et al*., 2016
-	atrazine and 2,4-d	Maize	Ondo State	South West	Akadiri *et al*., 2017
-	Cinosulfuron, prosulfuron, butachlor, prosufuron, and propanil	*Oryza sativa*	Kaduna State	North West	Haruna *et al.,* 2017
Vestermine®, Ricepro® and Bracerplus®	cyhalofop-butyl 12 % + bspyrbac-sodium 4 %),	*Oryza sativa*	Niger State	North Central	Mohammed *et al.,* 2022

	propanil, *2,4 D isobutyl ester*				
-	Metolachlor and butachlor	Sesame	Borno State	North East	Imoloame *et al.*, 2010
-	Trifluralin, metolachlor, clethodim, quizalofop-P-ethyl, and oxyfluorfen	*Glycine max*	Oyo State	South West	Aluko *et al.,* 2003
Paraforce®, Force Up®, Round Up®, Weed Crusher® and Nwurawura®	Glyphosate, atrazine paraquat dichloride, diamino-1,3,5-triazine, Isopropylamine		Oyo State	South West	Adesina *et al.,* 2024
-	metolachlor, butachlor and pendimethalin	Groundnut	Adamawa State	North East	Koroma *et al.,* 2021
-	Diuron, Indaziflam, Ixoxaflutole, Flumioxazin + Pyroxasulfone, Sulfentrazone, S-Metolachlor + Atrazine	Cocoyam	Oyo State	South West	Adewumi *et al.,* 2024
-	nicosulfuron and bentazone	Maize	Adamawa State	North East	Tizhe *et al.,* 2023
Xtra force®, 3-maize force®, pre maize®, guard force®	atrazine	Maize	Oyo State	South West	Olabode *et al.,* 2021
-	Glyphosate	Yam	Kogi State	North Central	Ajanya *et al.,* 2014
Diuron®, Goal tender®, Liberator Forte®, Codal Gold®, and Primextra Gold®	Oxyflurfen, Diuron, Flufenacet + diflufenican flurtamone, Prometryn + S – metolachlor, S – metolachlo + atrazine	Cocoyam	Abia State	South East	Cyprian and Onuba, 2019
-	Metolachlor, diuron, pendimethalin	*Glycine max*	Kwara State	North Central	Imoloame , 2014
Lasso 480EC Codal 400EC Cotoprim 425EC	Fluometuron, metolachlor, Fuazifop-butyl,	*Gossypium hirsutum*	Kaduna State	North West	Dadari and Kuchinda, 2004

Cotoran-Multi 500EC Dimepax 500EC Fusilade 125EC Karmex 80WP Dual 500EC	Dimethametryne, alachlor, terbutryne, diuron				
-	Atrazine and glyphosate	*Zea mays*	Taraba State	North East	Abakura *et al.,* 2015
-	*Butachlor and diuron*	Sesame	Adamawa State	North East	Audu *et al.,* 2021
-	Atrazine	Maize	Rivers State	South South	Gbaraneh and Briggs, 2021
-	Alachlor and metolachlor	Groundnut	Niger State	North Central	Lagoke *et al.,* 1981
-	Atrazine and Paraquat	Maize	Kano State	North West	Omar and Tasi'u, 2020
-	Atrazine and raft	Eleusine coracana	Kaduna State	North West	Gani and Umar, 2023
-	Atrazine	*Dioscorea alata*	Oyo State	South West	Olabode *et al.,* 2015
-	Chlorthaldimethyl	*Allium cepa*	Kaduna State	North West	Sinha and Lagoke, 1983

Human health

At Jos University Teaching Hospital, Adoga *et al*. (2018) found that farmers (11 males and 5 females) comprised the majority of patients who had been exposed to pesticides, herbicides, and chemical fertilisers, including nitrates, which are used to increase agricultural yield. The study found that the use of these agrochemicals was associated with an elevated risk of malignancies of the sinonasal region.

Oluwole and Cheke (2009) interviewed 150 farmers in Ekiti State, 93.3% of whom were male and had an average age of 55 years. These farmers reported experiencing a range of health issues, such as headaches, nausea, vomiting, eye irritation and skin problems. Most respondents (91.3%) reported that they or a family member had encountered health problems associated with pesticide use, either during or after pesticide application. However, they reported that the misuse and abuse of herbicides caused these health issues.

Environmental health

Only five investigations (Jatau *et al*., 2021; Lawrence *et al*., 2015; Olatoye *et al*., 2021; Osesua *et al*., 2017; Owagboriaye *et al*., 2022) examined herbicide residues in water (*Table 3*). Lawrence *et al*. (2015), Aliyu *et al*.

(2015), and Osesua *et al*. (2017) found atrazine and heptachlor in water and sediment samples in Sokoto State. Owagboriaye *et al*. (2022) measured the atrazine content of water sources in six Ogun State communities: Ago-Iwoye, Ijebu-Igbo, Oru, Ilaporu, Awa, and Mamu. The hazard index (HI) values for atrazine's non-carcinogenic effects on all groups, including children and adults, were below the regulatory threshold when it came to contact with the skin or consumption. In contrast, Jatau *et al*. (2021) found high herbicide residues that were higher than the ADIs and MRLs set by the WHO and FAO.

Mbuk *et al*. (2009) discovered that the use of herbicides, such as paraquat and glyphosate, particularly glyphosate, on fields may eventually cause leaching that reduces the soil's water-soluble K^+ and Mg^{2+} contents. Frequent herbicide application will enhance the availability of these metals for plant absorption, leading plants grown in these soils to eventually exhibit higher concentrations of these metals, which could potentially have harmful effects (Mbuk *et al*., 2009). The amount of iron (Fe), manganese (Mn), cadmium (Cd), and lead (Pb) in the surface water of herbicide-treated fields was higher than what the WHO considers safe for farming and living (Oyegoke *et al*., 2017).

Herbicides can alter the soil and the overall population of soil microorganisms, particularly when administered more than the advised dosage and for an extended period (Ayansina and Oso, 2006; Best-Ordinioha *et al*., 2016; Emurotu and Anyanwu, 2016; Gbarakoro and Zabbey, 2013; Oladele and Ayodele, 2017; Orji *et al*., 2017; Ngozi *et al*., 2020; Tudararo-Aherobo and Ataikiru, 2020; Ubogu and Akponah, 2022). Soil samples included residues of 2,4-D and 4,4-bipyridine but not at high enough concentrations to have a significant negative impact on pollution (Gudam *et al*., 2021). Atrazine residues were found in Fadama soil at Plateau State in higher concentrations than other herbicides, according to Gushit *et al*. (2012). Higher imazaquin and pendimethalin concentrations stop nodulation, nitrogen fixation, and the growth of vesicular-arbuscular mycorrhizal fungi in cowpea and soybean (Chikoye *et al*., 2014). According to Adesina *et al*. (2024), the herbicides monitored in Oyo State, such as aldrin and d-BHC, exceeded the regulatory thresholds set by European standards, presenting hazards to farmers, consumers, and ecosystems.

Abah *et al*. (2013b) and Onasanya *et al*. (2021) found that the attempt to improve cassava agricultural output through the inappropriate use of chemical fertilisers and herbicides led to the accumulation of trace metals in soils and cassava roots. Consumption of cassava roots containing excessive amounts of trace metals may expose people to the dangers of food poisoning. Abah *et al*. (2013a) demonstrated that the intensive use of chemical fertilisers and herbicides in bean–yam intercropping as well as in bean cultivation can result in the accumulation of heavy metals in soils and bean seeds. High levels of cadmium, pH, iron, magnesium, and chlorine exceed the established threshold limit due to herbicide application and are significant contributors to lake pollution, posing potential current and future issues.

Ighere (2020) showed that the pH levels of herbicide-treated (HT) soils are lower than those of non-treated soils. Furthermore, HT soils exhibit low soil air, inadequate drainage, high water retention capacity, and a scarcity or absence of soil organisms. The organic matter content of soils treated with herbicides significantly decreased compared to untreated soils. When herbicides, such as atrazine, primextra, paraquat, and glyphosate, were used in the study by Sebiomo *et al*. (2011), soil dehydrogenase activity decreased significantly compared to when the plants were not treated.

In contrast to the long-lasting presence of atrazine in the soil, as documented by many scientists, Sangoyomi *et al*. (2014) found that plots treated with atrazine in four planting seasons had the highest number of fungal genera by the end of the third survey session. The compounds Gramoxone, Dacthal, Preforan, and Dual did not have any negative impacts on soil microorganisms (Ekundayo, 2003). Tudararo-Aherobo and Ataikiru (2020) found that herbicides had no effect on pH, total organic carbon, or nitrate levels. However, extended herbicide use had a detrimental effect on bacterial and fungal populations. Musa and Salem (2020) found no impact of herbicide application on the variability of soil physical characteristics across several sites. Furthermore, the data showed that locations without herbicides experienced elevated initial and cumulative infiltration rates. According to Saleh *et al*. (2023b), using herbicides at the field-recommended rate did not hurt the bacterial load at a site in Kaduna State. It can be deduced from these findings that although herbicide application does contribute to the agricultural process, it also has ecological consequences, adversely affecting soil fertility and microorganisms and disturbing the soil ecology.

Animal health

Glyphosate can destroy beneficial arthropods, such as termites, according to Ekaye *et al*. (2022). This phenomenon is particularly evident at concentrations exceeding the recommended levels. Oluwole and Cheke (2009) found that farmers observed a decline in the quantity of beneficial insects and other animals. Reports of abnormal drops in the populations of birds and mammals near their fields corroborated this. Similarly, Ubani *et al*. (2020) found that the herbicide samples (paraquat dichloride, glyphosate, butachlor, and 2, 4-D amine 720G/L) decreased the acetylcholinesterase activity of *Achatina achatina* and that herbicides were detrimental to snails collected from Enugu State.

Another area of concern has been the impact of paraquat on aquatic species in the Nigerian food chain (Shallangwa and Auta, 2008). Researchers have linked their use to the deaths of catfish (Kori-Siakpere *et al*., 2007) and Nile tilapia (Ajani *et al*., 2007; Fidelis *et al*., 2012). According to Alarape *et al*. (2023), glyphosate residues were present in all 75 fish tissue samples collected from specific fish markets in the city of Ibadan. Furthermore, all residue concentrations were higher than the suggested MRL of 0.01 mg/L. Akan *et al*. (2019) and Olatoye *et al*. (2021) identified glyphosate, atrazine, butachlor, metolachlor, paraquat, propachlor, propanil, and alachlor in fish samples.

Table 3 – Studies that detected herbicide concentrations in the environment

Herbicide	Region	Zone	Values detected	US EPA limit	Reference
Atrazine	Ogun State	South West	0.01mg/L, 0,03mg/L, 0.04mg/L, 0.08mg/L	0.03mg/L	Owagboriaye *et al*., 2022
Butachlor, glyphosate, paraquat, propachlor, propanil, alachlor, metalochlor, atrazine	Adamawa State	North East	0.16mg/L (B), 0.23 mg/L (G), 0.19 mg/L (Pa), 0.21 mg/L (Pr), 0.15 mg/L (At), 0.16 mg/L (Pro), 0.12 mg/L (Ala), 0.12 mg/L (Meta)	0.1 mg/L (B), 2.0 mg/L (G), 0.5 mg/L (Pa), 0.05 mg/L (At), 2.0 mg/L (Pro), 0.2 mg/L (Ala), 0.05 mg/L (Meta)	Jatau *et al*., 2021
Atrazine	Lagos State Ogun State Oyo State	South West	1.8µg/kg, 1.4 µg/kg, 1.6 µg/kg	6 µg/kg	Olatoye *et al*., 2021
Paraquat and glyphosate	Benue State	North Central	-	-	Mbuk *et al*., 2009
Butachlor and bispyribac – sodium sc	Ebonyi State	South East	-	-	Orji *et al*., 2017
Glyphosate	Rivers State	South South	-	-	Best-Ordinioha *et al*., 2016
Atrazine, paraquat dichloride, 2,4-dichlorophenoxy acetic acids and oxadiazon	Plateau State	North Central	-	-	Gushit *et al*., 2012
4,4 –bypridine and 2,4 –d	Plateau State	North Central	-	-	Gudam *et al*., 2021
Lindane, heptachlor, aldrin, endosulfan, carbofuran, 4,4-ddt, dieldrin, endrin	Edo State	South South	-	-	Edo-Taiwo and Aisien, 2023
Imazaquin and pendimethalin	Kaduna State	North West	-	-	Chikoye *et al*., 2014
Atrazine and metolachlor	Oyo State	South West	-	-	Ayansina and Oso, 2006

Additionally, Nwani *et al*. (2013) showed that butachlor exhibited toxicity towards *Tilapia zillii*. Erhunmwunse *et al*. (2014) found that post-juvenile African catfish (*Clarias gariepinus*) had different amounts of glyphosate-herbicide in their brain tissue. *Clarias gariepinus* plants were exposed to low levels of paraquat in the lab, which caused macrocytic-normochromic anaemia (Abubakar and Ibrahim, 2022). According to additional research (Ayanda *et al*., 2015; Babatunde *et al*., 2021; Omitoyin *et al*., 2006), paraquat is toxic to aquatic life, worsens environmental deterioration, produces pollution, and jeopardises the sustainability of the ecosystem. Olaleye *et al*. (1993) found that fish returned to the area in Kofawei Creek, Ondo State, where herbicides had been used to eliminate water hyacinth. In this study, the researchers found that there was an increase in the number of fish compostition at the treated area after herbicidal treatment.

The combination of pesticides sprayed by farmers on cocoa farms builds up in the environment and in the tissues of amphibians, according to Edo-Taiwo and Aisien (2020). The pesticide concentrations in various samples, including amphibian tissues, silt, and soil, generally followed the same trend.

Biocontrol

As indicated by Fayinminnu *et al*. (2013), crude cassava water extract from bulk, MS6 and TMS 30555 varieties was able to successfully operate as a post-emergence herbicide against weeds during the crucial early growth stage of cowpea. This study also showed that crude cassava water extract, due to its widespread availability and rapid biodegradation, could serve as a viable substitute for synthetic herbicides.

In a study conducted in Ogun State by Fadeyi *et al*. (2023), the application of moringa leaves inhibited weed growth and survival. Eke-Okoro*et al*. (2017) found that intercrop establishments with cucumbers and cassava had much lower weed populations and dry weights than establishments with only cassava, regardless of the type of cassava grown or how many cucumbers were planted.

Aso *et al*. (2021) concluded that their chosen bacterial strains could be used for bioremediation of glyphosate-contaminated soil, sediments, and ponds over a wide range of environmental conditions. Glyphosate-utilising bacterial species, including *Bacillus cereus*, *Stenotrophomonas maltophilia*, and *Enterobacter aerogenes*, were optimised to tolerate the pesticide concentration at the different parameters selected. According to Saleh *et al*. (2023a), the bacteria *Aeromonas* sp. and *Acidovorax* sp. can be used to biodegrade glyphosate and paraquat; however, more research is needed to determine whether these microorganisms can also break down other herbicides.

Olu-Arotiowa *et al*. (2019) reported that the use of *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Aspergillus niger*, and chicken droppings as bioaugmentation and biostimulation agents increased or sped up the rate of atrazine biodegradation in soil and, consequently, its removal from contaminated soil.

In their study, Makut and Ibrahim (2021) found that the most common microorganisms in herbicide-contaminated farmland in Keffi were

Pseudomonas aeruginosa strain CIFRI DTSB1 and *Entrobacter asburiae* RD-DAROS-04. They also found fungus species, such as *Aspergillus flavus* and *Fusarium redolens*, degraded herbicides in the region. Sebiomo and Banjo (2020) demonstrated that microorganisms effectively utilised herbicides as a carbon source and for their developmental processes.

Therefore, we can use native indigenous microorganisms for bioremediation of herbicide-contaminated soils. *Bacillus safensis* strain BUK_BCH_BTE6, discovered in Kano, digested 88.85% of 400 mg/L atrazine and to tolerate 2 ppm heavy metals, according to Muhammad *et al.* (2023). Because it is an effective and highly tolerant atrazine degrader, we can use this isolate for the bioremediation of atrazine-polluted sites. Moneke *et al.* (2010) isolated and identified two bacterial species, *P. fluorescens* and *Acetobacter* sp., capable of biodegrading glyphosate. These isolates' ability to efficiently metabolise glyphosate provides a solution for removing these chemicals from the environment. Therefore, the isolates' ability to endure and proliferate in the presence of elevated levels of herbicide makes them ideal for bioremediation of glyphosate-contaminated habitats.

Adewuyi and Offar (2021) found that the factors influencing farmers' acceptance of new technology included the farmers' age, educational attainment, farm size, access to extension services, farming experience, and cooperative society membership. These findings suggest increasing farmers' awareness of bio-herbicide technology.

DISCUSSION

Of all pesticides, herbicides comprise the highest proportion (47.5%), followed by insecticides (29.5%), fungicides (17.5%), and other insecticides (5.5%) (Sharma *et al*., 2019). About 33% of agricultural products use pesticides in their production. More than 80% of pesticides used to protect crops are herbicides (Ferrero and Tinarelli, 2007; Sitaramaraju *et al*., 2014). There have been reports of negative environmental effects from HU. Offsite transportation, coupled with the growing use of herbicides with high potential mobility, can lead to significant environmental issues. Herbicide use to manage weeds in residential areas of urban environments has expanded significantly in recent years, particularly in Nigeria (Bulu *et al*., 2019), where 99% of pesticide-related deaths occur (Gunnell *et al.* 2007; Ojo, 2016). One million people worldwide lost their lives because of pesticide poisoning in 1999. According to the WHO, 3 million people are poisoned by pesticides annually (OECD, 2008; WHO, 2016). Ghazi *et al.* (2023) discussed at length the different ways that herbicides affect people's health.

In many countries, humans depend on surface freshwater for drinking, enjoyment, and the production of economically important foods (Wilson and Carpenter, 1999). Human activities have put increasing pressure on waterbodies. One such pressure is the contamination of these waterbodies by a range of inorganic and organic pollutants from farmlands, which are farm inputs that typically wash into these waterbodies and build up to the detriment of aquatic life (Shushkova *et al*., 2012). Herbicides make up most of these organic pollutants (Dorigo *et al*., 2007). The maximum residual level of organochlorine pesticides in soil, sediment, and amphibian tissues is currently unknown in Nigeria (Egbe *et al*., 2021).

Several studies have also linked herbicides to the quantitative and qualitative loss of significant soil bacteria involved in decomposition, nitrogen cycling, fixing, and other beneficial soil activities (Min *et al*., 2002). We have a poor understanding of how herbicides affect microbial diversity, nitrification, denitrification, sulphur oxidation, plant nutrient mineralisation, crop residue decomposition, and the quantitative and qualitative aspects of soil organic matter equilibrium (Barman and Varshney, 2008). To lower risks, it is advisable to discourage the system from weighing the costs and advantages of using fertilisers and herbicides that include harmful chemicals and to promote research into the development of safer alternatives (Adoga *et al*., 2018).

The socioeconomic factors that affect herbicide use by maize farmers in Kaduna State were household income and educational attainment; the institutional factors that affected herbicide use by the farmers were membership in associations and extension contacts (Oyinbo *et al*., 2013). A misconception exists among crop farmers in Ikorodu regarding the inherent risks associated with improper HU, both for their own well-being and the environment (Falade *et al*., 2022). The people tasked with educating farmers ought to put more effort into teaching them, particularly when it comes to teaching them how to use herbicides responsibly and not to squander them because doing so will reduce the efficiency of their output (Nwahia *et al*., 2020).

Herbicides have significant and concerning effects on human health. The consumption of contaminated food, prolonged exposure to toxic compounds, and environmental exposure can all be harmful to one’s health. It is imperative to determine the effectiveness of herbicide products for the intended purposes while simultaneously safeguarding pesticide users, consumers, crops, livestock, and the environment. In Nigeria, agrochemicals are widely utilised but are not well regulated. Regulation of any kind does not eliminate the difficulty of monitoring and evaluation. Serious attempts are underway to establish sensible policy standards as environmental preservation gains increasing popularity.

Developed nations, such as the United States, Canada and the European Union (EU), have enacted new legislation restricting agrochemical use (Nnamonu and Onekutu, 2015). The EU only releases active substances registered on its list of approved active substances into the environment, which each EU Member State has subsequently authorised as plant protection products. Authorisation is granted only if proposed uses are not expected (or known) to have harmful effects on environmental, animal, or human health (Storck *et al*., 2017). The Federal Ministry of Agriculture and Rural Development in Nigeria (FAO, 2024) developed an agriculture promotion policy. The policy aims to enhance access to information on, promote the use of safe alternatives to highly hazardous pesticides (e.g., organic (natural) pesticides), improve regulation, inspection, and enforcement of rational agrochemical use, and improve quality assurance and residue testing. In addition, the Nigerian National Assembly enacted a biosafety law in 2015 that promoted the growth of genetically modified (GM) crops (Kargbo *et al*., 2020).

The global usage of pesticides and herbicides has significantly decreased with the introduction of GM crops, which have a positive effect on human and animal health as well as the environment (Brookes and Barfoot, 2017). Brookes and Barfoot (2017), which used the Environmental Impact Quotient to compare the effects of pesticides and herbicides on conventional and genetically modified farming systems, showed that the traits of GM crops greatly reduce the damage they do to the environment when they are used.

However, despite the policy's establishment, there are no strict laws guarding herbicide use in the country. We suggest implementing specific regulations for herbicide use in areas, especially those near drinking water, amending the country's constitution to strengthen the foundations of herbicide risk assessment, promoting scientific knowledge to enhance societal acceptance of the herbicide authorisation process, conducting ongoing environmental risk assessment studies, and establishing clear policies for the development, regulation, and implementation of biopesticides in Nigeria. Lastly, the HU database should be established in Nigeria.

Microorganisms, such as pathogens and other bacteria, or phytotoxins generated from microbes, insects, or plant extracts, form the basis of bioherbicides, a natural weed control method (Bailey, 2014). Recently, Hoagland *et al*. (2007) recognised bioherbicides as an essential component of weed management; however, Singh *et al*. (2009) cautioned against exclusively substituting them with chemical herbicides.

As scientific studies increasingly demonstrate their effectiveness, the use of bioherbicides, perceived as safer and "greener," has gained traction (Hasan *et al*., 2021). When rules severely restrict or forbid herbicide use, bioherbicides will be invaluable in managing weeds in regions where environmental preservation is the major goal of management, and herbicides are ineffective (Kremer, 2005).

To preserve human health, it is imperative to limit herbicide use through the adoption of more sustainable and alternative farming practices, such as integrated pest control and organic farming. Raising awareness of the risks associated with pesticides and the benefits of environmentally friendly farming methods among farmers, consumers and legislators is also essential to creating a safer and healthier environment for all (Rathee and Dubey, 2023). To prevent herbicide resistance, lower production costs, and boost crop output in organic horticulture, integrated weed management systems can incorporate bioherbicide technology (Cai and Gu, 2016).

RECOMMENDATIONS

· Farmers must use caution and adhere to the recommended dosage, application method, and other guidelines while applying herbicides.

· Other methods should be used to remove weeds, instead of using herbicides unless required.

· To protect farmers and the environment, appropriate and effective government regulations should be in place regarding the herbicides that farmers can use in the nation.

· Indigenous private sector participation in the development, testing, and distribution of botanicals ought to be encouraged.

· To ensure that the public benefits as much as possible from these locally accessible resources, the government should create policies that support and safeguard regional businesses that might be engaged in the processing and sale of botanical pesticides (Nnamonu and Onekutu, 2015).

· To safeguard crops, Nigeria now uses many hazardous pesticides. The rules prohibiting these types of pesticides are either completely or severely restricted; however, they are not upheld. The number of pesticide-related deaths will decline with the tight enforcement of this rule and the planned use and promotion of green insecticides, which are far safer for the environment, food consumers, and applicators (Lale, 2002).

· To raise public understanding of the alternatives for synthetic pesticides, the Nigerian government should support vigorous enlightenment programs in the public and commercial sectors (Nnamonu and Onekutu, 2015).

· The Nigerian cropping system should support and encourage the use of organic weed control measures. Lastly, Nigerian farmers should be educated about the importance of implementing organic weed control measures, which are intended to improve soil fertility, eliminate environmental pollution and soil degradation, provide healthy farm produce for humans and their animals, and effectively control weeds (Ansa and Wiro, 2020).

CONCLUSIONS AND FUTURE DIRECTIONS

Nigeria is known for its extensive use of herbicides. Despite the positive impact these chemicals have on crop production, we should not overlook their harmful effects on non-target organisms. Scientists, medical professionals, and other interested parties should collaborate to develop a strategy to reduce the use of these harmful substances in Nigeria. The concept of "One Health" refers to the connection between human, animal, and environmental health. This strategy is required to reduce the risk associated with herbicide use. The focus should be on creating safer weed control strategies. In addition, awareness initiatives must concentrate on educating rural farmers and distributors regarding safe HA techniques and the environmental consequences of misuse.

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