# INFLUENCE OF HANDLING PRACTICES ON PESTICIDE RESIDUES AND GLYCOALKALOID LEVELS IN POTATO (*Solanum tuberosum* L.) TUBERS IN NYANDARUA COUNTY, KENYA

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## DECLARATION AND RECOMMENDATION

### Declaration

This thesis is my original work and has not been presented in this university or any other for the award of a degree

Signature: Date: 24/09/2025

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### Recommendation

This thesis has been submitted with our approval as university supervisors.

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## ABSTRACT

The safety of potato (*Solanum tuberosum* L.) products is of concern in Kenya due to poor handling practices along the value chain. This study determined the effect of handling practices on pesticide residues and glycoalkaloid levels in potato tubers. A cross-sectional survey of 275 farmers and 110 traders in Nyandarua County, Kenya was conducted to assess potato handling practices along the value chain using semi-structured questionnaires. Based on the handling practices, *Shangi* variety potato samples were collected at the farmgate (n=16) and at the market (n=24), analysed for pesticide residues and glycoalkaloid levels respectively. Afterwards, the effect of various processing methods was determined. The separation and quantification of the target pesticides (imidacloprid, fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, 2,4-D, atrazine, metolachlor, glyphosate, azoxystrobin, mancozeb, metalaxyl) was done by gas chromatography-mass spectroscopy and liquid chromatography-tandem mass spectrometry system. Pesticide application rates based on agro vets' instructions resulted in the highest herbicide residue levels (4.63 μg/kg). Following advice from other farmers led to the highest fungicide (49.55 μg/kg) and insecticide (24.65 μg/kg) residue levels. Potatoes exposed to light had the highest levels of glycoalkaloid (834.03 mg/kg dry weight), while those with mechanical injury had the lowest levels (357.04 mg/kg dry weight). Different processing methods showed a significant difference in pesticide residue and glycoalkaloid levels in potato tubers. Frying effectively reduced most pesticide residues (92.37% to 16.41%), α-chaconine (51.72%), and α-solanine (41.79%), while roasting was the least effective (reducing pesticides by 73.39% to 12.46%). Steaming resulted in the lowest decrease of α-chaconine (9.13%) and α-solanine (6.34%). This study has shown that improper handling practices result in high pesticide residue and glycoalkaloid levels in tubers, posing a health threat to consumers. Therefore, awareness of proper handling practices is essential for consumer safety.

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| | |
|---|---|
| **AOAC** | Association of Official Analytical Chemists |
| **CIP** | International Potato Centre |
| **CRD** | Completely Randomised Design |
| **FAO** | Food and Agriculture Organisation of the United Nations |
| **GAs** | Glycoalkaloids |
| **KES** | Kenya Shillings |
| **MRLs** | Maximum Residue Limits |
| **SDGs** | Sustainable Development Goals |
| **WHO** | World Health Organization |

# CHAPTER ONE
# INTRODUCTION

## 1.1 Background information

Potato (*Solanum tuberosum* L.) is one of the most important non-cereal food crops in the world, ranking fourth after rice, wheat, and maize (Wang & Xie, 2022). The global annual production of potatoes is approximately 370 million metric tonnes (FAO, 2021). In Kenya, it is the second most important food security crop after maize, with the production capacity being approximately 2.8 million tonnes. The crop is mainly grown for both domestic use and as a source of livelihood. Its contribution to the economy of Kenya is close to KES 50 billion. Approximately 2.5 million people are employed along the value chain (National Potato Council of Kenya, 2021). The domestic demand for potatoes in Kenya is around 3.1 million tonnes, while only 2.8 million tonnes are available for utilization (Kenya National Bureau of Statistics, 2020). The increased demand for potatoes in Kenya is mainly driven by rapid growth in the urban population, changes in taste and preferences, and consumption habits (Wakaba *et al.,* 2022). As a result, the average consumption of potatoes per person has increased from 35 kg in 2019 to 63 kg in 2021 (Kenya National Bureau of Statistics, 2020; Kenya National Bureau of Statistics, 2022). This rise in demand has accelerated the growth of the potato processing sector, which now includes two hundred local processors handling more than 217.7 tonnes daily (Kenya National Bureau of Statistics, 2020).

In Kenya, the main areas where potatoes are grown include Meru, Narok, Nakuru, Bomet, Uasin Gishu, Nyandarua, Kiambu, Trans-Nzoia, Nyeri, West Pokot, and Elgeyo-Marakwet, with Nyandarua being the leading producer (Janssens *et al*., 2013; National Potato Council of Kenya, 2017). There are over fifty both local and improved varieties available in Kenya (National Potato Council of Kenya, 2017). Among these varieties, *Shangi* is the most commonly grown and consumed because it has a ready market, good cooking qualities, readily available seeds, high yield potential and matures early (Agong *et al*., 2021; Muthee *et al*., 2021).

There are various challenges affecting the potato value chain in Kenya, including pests and diseases (Mariita *et al*., 2016) and postharvest losses due to poor handling practices (Musita *et al*., 2019). Climate change has increased pests and disease prevalence and if not controlled, they can lead to 100% loss of yields (Awojobi, 2017; Mariita *et al*., 2016; Taiy, 2017). This has resulted to intensive pesticide usage to protect the crops for increased productivity to meet the rising demand. The pesticides commonly applied are synthetic pyrethroids, organophosphates, organochlorines and carbamates which belong to World Health Organization (WHO) class II (moderately hazardous). Although restricted/banned from use on food/ crops by the Pest Control and Products Board, some pesticides containing active ingredients such as the dimethoate and diazinon are still being used by some farmers (Oyoo *et al*., 2021).

In Kenya, the Pest Control Products Board (PCPB) which was established under the Pest Control Products Act CAP 346 of 1983 (PCPB, 2005) oversees the regulation of pest control substances. Despite the regulations, pesticide use in the country face many drawbacks including misuse, improper handling, occupational exposure, environmental pollution, deterioration of water quality, and food contamination with pesticide residues (Marete *et al.,* 2021). After application in the field, some pesticides which have longer half-lives get into the food chain in form of residues (Devi *et al*., 2018). The concentration gradient of the pesticide residues between the soil and potato tissues thermodynamically drives chemicals toward uptake into the potato tubers (Xiao *et al*., 2021). The residue concentration in plants depend on the number of applications in the agricultural field, application rates, application methods, and the interval between harvesting and pesticide treatment (Devi *et al*., 2018).

The Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have set maximum residue limits (MRLs) for every active ingredient present in the pesticides used in potato production to safeguard the health of consumers by ensuring that the food is safe (FAO/WHO, 2021). The range for the MRLs of pesticide residues is usually 0.01 to 10 mg/kg, which varies with the active compound present (Narenderan & Meyyanathan, 2019). Despite the establishment of the MRLs, pesticide residues beyond MRLs have been reported in potato tubers and products worldwide (López-Pérez *et al*., 2006; Soliman, 2001). On this note, potato producers should observe Good Agricultural Practices (GAPs) to guarantee that the levels of pesticide residues remain below the established MRLs when the potato tubers reach consumers at markets or retail outlets (FAO/WHO, 2018). This is because long-term dietary exposure to pesticide residues, including metolachlor, chlorpyrifos, glyphosate, atrazine, among others, has been associated with health problems such as birth defects, genetic defects, neurotoxicity, cancers, blood disorders, and endocrine disruption (Leong *et al*., 2020).

Poor postharvest handling is also a significant challenge affecting the potato value chain. Proper postharvest handling is important in preserving the safety and nutritional quality while reducing losses (Musita *et al*, 2019). In the Kenyan markets, almost a quarter of the potatoes are exposed to unfavourable temperatures, light, injuries or bruises, and other conditions that lead to increased levels of glycoalkaloids (Kaguongo *et al*., 2014). Glycoalkaloids belong to a family of steroidal natural toxic secondary metabolites present in all parts of the potato, and when ingested in large quantities, can be harmful to humans. In potatoes, α-solanine and α-chaconine are the most predominant, comprising 95% of total glycoalkaloid content (Nema *et al*., 2008). The rest, including β- and γ-solanines, β- and γ-chaconine, α- and β-solamarines, and demissidine, comprise only 5% (Omayio *et al*., 2016). Levels of total glycoalkaloids in selected potato varieties and advanced clones in Kenya under well-controlled conditions are within the range of 3.7 to 17.5 mg/100 g. This is below the maximum set limit of 20 mg per 100 g of tuber (Ginzberg *et al*., 2009; Kirui *et al*., 2009). However, poor handling might elevate the levels of these toxins beyond the set limits. An oral intake of 1 to 5 mg of glycoalkaloids per kilogram of body weight per day may result in mild or severe effects such as gastrointestinal disturbances and neurological disorders in humans (Hellenäs *et al.,* 1992; Schrenk *et al.,* 2020).

With the growing reliance on synthetic pesticides in potato production, poor postharvest handling practices and rising demand for potato products, there are increasing concerns about food safety issues in Kenya. Fresh potatoes are a significant diet and are consumed mainly as boiled, fried, baked or incorporated into traditional dishes (McEwan *et al*., 2021; Naziri *et al*., 2024; Tesfaye *et al*., 2010). They are subjected to many processes, including washing, peeling, blanching, baking, frying and other processes which may reduce some of the pesticide residues and glycoalkaloids (Liu *et al*., 2020; Velioglu & Yigit, 2020). Glycoalkaloids and pesticide residues are soluble in water hence some may be lost during processing (Kruma & Zarins, 2017; Velioglu & Yigit, 2020). Heat treatment has variable effects because glycoalkaloids such as α-solanine and α-chaconine are stable at high temperatures and decompose at around 170°C (Omayio *et al*., 2016). Upon heat treatment, pesticide residue concentration is altered through physicochemical processes such as thermal degradation, hydrolysis, volatilization, or concentration (Naman *et al*., 2022). The degree of residue alteration depends on pesticide's properties like volatility, solubility, lipophilicity, and thermal stability, as well as processing parameters like temperature, duration, and medium composition, with some pesticides potentially forming toxic metabolites that pose greater hazards (Liu *et al.,* 2020; Uygun *et al*., 2009). Since processed potato products are consumed widely, understanding how common cooking methods affect the levels of pesticide residues and glycoalkaloids is important in safeguarding the health of consumers.

There is limited data available on how handling practices affect the levels of pesticide residues and glycoalkaloid accumulation in potato tubers in Kenya. Thus, the consequences or their contribution to the safety of potato products are unknown to many, especially with the prevalence of processed potato products in consumer diets. This study, therefore, sought to address the food safety aspect regarding pesticide use and postharvest handling practices along the potato value chain in Nyandarua County, Kenya's leading potato-producing region. This is crucial for ensuring safe potato products ultimately reach consumers.

## 1.2 Statement of the problem

The safety of potato products in Kenya is a growing concern because of the increased application of pesticides during production and poor postharvest handling practices along the value chain. These factors increase the risk of pesticide residues and glycoalkaloids accumulation in the tubers, which are hazardous to the health of consistent consumers. Even with the increasing consumption of potato products, information on pesticide residues and glycoalkaloid levels in potato products in Nyandarua County is limited. Therefore, the purpose of this study was to establish how pesticide residues and glycoalkaloid levels in potato tubers are influenced by on-farm pesticide practices and postharvest handling practices along the value chain. The study also aimed to determine the effect of various common processing methods on the pesticide residue and glycoalkaloid levels in potato products.

## 1.3 General objective

To contribute to food safety by assessing the influence of handling practices and common processing methods on the level of pesticide residues and glycoalkaloids in potato tubers.

### 1.3.1 Specific objectives

i. To evaluate potato handling practices along the potato value chain in Nyandarua County.

ii. To determine the effect of the handling practices on pesticide residue and glycoalkaloid levels in potato tubers.

iii. To determine the effect of common processing methods on pesticide residue and glycoalkaloid levels in potato products.

### 1.3.2 Research questions

i. What are the potato handling practices along the value chain in Nyandarua County?

ii. Do handling practices have a significant effect on the pesticide residue and glycoalkaloid levels in potato tubers?

iii. Do common processing methods have a significant effect on the pesticide residue and glycoalkaloid levels in potato products?

## 1.4 Justification

Potato has become a significant part of the diet in Kenya. Its demand has been growing fast due to rapid urbanization and the growth of fast-food industries. There is increased use of pesticides by most potato farmers during production for crop protection to meet the demand. In addition, potatoes in Kenya are exposed to unfavourable conditions that may favour glycoalkaloid accumulation during postharvest handling. This threatens the safety of potato products which has not received much attention in Kenya. Therefore, this research determined how handling practices affect the pesticide residues and glycoalkaloid levels in potato tubers in Nyandarua County, which is Kenya's leading potato-producing County. The information of the study will be useful in educating potato value chain actors on appropriate practices for safe potato products. In turn, this will contribute towards the realization of food security and good health and well-being Sustainable Development Goals (SDGs). Also, it will be key in advancing the food security pillar of Kenya's Bottom-Up Economic Transformation Agenda Model.

## 1.5 Scope and limitations

This study was limited to Nyandarua County and *Shangi* potato variety only. Given the potential variability in handling practices along the potato value chain, research in other potato-growing regions and the incorporation of additional factors, such as different potato varieties, could be essential.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Potato production and utilization in Kenya

Globally potato is one of the most significant staple food crops. In Kenya, potato is cultivated by over 800,000 farmers with the total area under farming being approximately 212, 976 ha (FAO, 2021). More than 90% of farmers grow potatoes on small pieces of land measuring less than 0.2 hectares. The crop is one of the five key value chains prioritized to ensure transformation of the agricultural sector while promoting inclusive growth under the food security pillar of the Kenya's bottom-up economic transformation agenda (State Department for Economic Planning, 2024). As reported by National Potato Council of Kenya (2021), potato industry in Kenya generates over KES 50 billion annually, ranking it as the country's most valuable crop after maize. Its cultivation is mainly carried out in areas with high-altitude (mostly 1,500 and 3,000 meters above sea level) including Eastern, Rift Valley and the Central areas of Kenya. The counties with the highest production of potatoes include Bungoma, Nyandarua, Elgeyo-Marakwet, Meru, Narok, Nakuru, Bomet, and West-Pokot (Janssens *et al.,* 2013). More than fifty potato varieties are available in Kenya (National Potato Council of Kenya, 2017). The commonly cultivated and consumed varieties are *Shangi, Kenya mpya, Dutch Robjin, Tigoni,* and *Asante* amongst others (Kaguongo *et al*., 2014).

According to the International Potato Center (CIP) (2019), the largest share of the cultivated potatoes is usually processed into food and non-food products, animal feed or preserved as seed for the next planting season. Over time, the consumption of potatoes has gradually shifted to value-added processed products. The shift is largely attributed to rapid population growth, urbanisation, and the evolving lifestyles especially among younger individuals (Abong' *et al*., 2015; Rytel *et al*., 2005). In Kenya, fresh potatoes are a significant diet contributing one-third of the nation's overall dietary energy consumption, and serves as a key value chain for household income generation (Wakaba *et al*., 2025). The tubers are consumed in different forms including; boiled, baked, roasted or fried state or incorporated into traditional dishes (CIP, 2019; Tesfaye *et al*., 2010). Processing enhances the value of the tubers by extending its shelf life and reducing post-harvest losses. It also ensures that there is a wide range of products such as crisps, *French Fries* (commonly referred to as chips), dehydrated potato flakes, potato flour, chilled peeled potatoes, canned potatoes and alcohol for human consumption among others (CIP, 2019; Kot *et al.*, 2020; Tajner-Czopek *et al*., 2021).

## 2.2 Challenges along the potato value chain

There are various challenges facing potato value chain in Kenya with pests, diseases and postharvest management being the most important. Other constraints include limited access to disease-free certified seeds, climate change, poor agronomic practices, weeds, low fertility of the soil and high cost of inputs such as fertilizers among others (Agong *et al*., 2021). These factors contribute to significant losses before and after harvest leading to reduced yields and farmer incomes. (Nema *et al.,* 2008).

### 2.2.1 Pests and diseases affecting potato crops in Kenya

Potato crops' quality and quantity of the yields is negatively affected by pests and diseases. In Kenya, main potato diseases such as late blight (*Phytophthora infestans*), bacterial wilt (*Ralstonia solanacearum*), potato cyst nematodes and viruses can cause 100% yield loss when not properly controlled (Mariita *et al*., 2016; Mumia *et al*., 2018; Onditi *et al*., 2021).

Late blight, one of the major global destructive diseases in potato crops is caused by the polycyclic pathogen *Phytophthora infestans* (Mont.) (de Vries *et al*., 2018). The disease attacks the crops at any stage of growth when environmental conditions are favourable, particularly relative humidity of 90% and temperatures between 7.2 and 26.6$^{o}$C (Lal *et al*., 2018). It is considered as the most demanding and costly disease of potato crops because of the losses it causes in the field and postharvest as well as the costs of its management in the field (Cooke *et al*., 2011). In Kenya, it causes losses of about 30 to 60% and can result in up to 100% yield loss if no interventions are put in place on time (Mariita *et al*., 2016). Potato varieties with moderate resistance towards blight disease experience yield losses ranging from 40 to 70% while more susceptible varieties may suffer losses around 50 to 70% when the crops are managed well even without using fungicides (Ojiambo *et al*., 2001; Rahman *et al*., 2008).

Bacterial wilt, the most important disease after late blight in Kenya is caused by *Ralstonia solanacearum* (Kaguongo *et al*., 2010). The pathogen is commonly spread through contaminated run-off water, seeds, tools used in the farm, and soil (Jibat *et al.,* 2018). The disease has spread to over seven out of ten potato-growing areas' farms resulting to yield losses estimated between 50 and 100%. Infected plants start to wilt and dries up, tubers develop brown to black discolouration and finally rot hence reducing the tuber quality and yields (Khairy *et al*., 2021). Management of this disease is challenging because the pathogen exhibits extensive genetic diversity and has many hosts spanning over 200 plant families including weed species (Chebet *et al*., 2021).

A number of nematode species negatively impact potato crop production (Medina *et al*., 2017). These pests feed on the tubers of the potato crops disrupting the ability of the crop to absorb and accumulate water and nutrients. The infested tubers always develop lesions, decay and shrivel resulting to loss of the yields (Coyne *et al*., 2018; Hay *et al*., 2016). The most economically important nematodes are the potato cyst nematodes (*Globodera spp.)* and root-knot nematodes (*Meloidogyne spp*.). The only types of cyst nematode species prevalent in all potato-producing counties in Kenya are *Globodera rostochiensis* and *Globodera pallida* (Mburu *et al*., 2018; Mburu *et al*., 2020). They decrease potato tuber yields, and quality, change the physical and chemical qualities and make them unmarketable. This leads to losses of up to 70% and 100% loss in some instances (Mbiyu *et al*., 2022; Mburu *et al*., 2020) depending on the population density of the nematodes, number of reproduction cycles per year, potato crop season length, planting time, moisture of the soil, temperature of the soil, structure of the soil and characteristics of the host (Sparkes, 2013). The root-knot nematodes prevalence is also widespread in Kenya with *M. hapla, M. incognita, M.javanica, M. acronea*, *M. africana,* and *M. kikuyensis* being the species that are frequently reported (Karuri *et al*., 2017).

Viral infections are also among the significant category of potato crop's vector and seed-borne diseases. Among the 40 viruses that can infect potatoes (Whitfield *et al*., 2015), six viruses including potato virus S (PVS, Carlavirus), potato virus Y (PVY, genus Potyvirus), potato leaf roll virus (PLRV, Polerovirus), potato virus A (PVA, Potyvirus), potato virus X (PVX, Potexvirus), and potato virus M (PVM, Carlavirus) are very important in Kenya with a prevalence of 72.9% (Onditi *et al*., 2021). Same trends have been observed in the bordering countries like Tanzania, Ethiopia and Uganda (Gildemacher *et al*., 2011; Priegnitz *et al*., 2019). All the six potato viruses are tuber-borne and are transmitted by some aphid species except PVX which is spread through contact (Whitfield *et al*., 2015) and PVS, which might also have aphid-transmitted variants (Kreuze *et al.*, 2020). Some of the aphid species that transmit potato viruses have been found to have a high incidence in Kenya's potato-growing regions (Muthomi *et al.*, 2009; Olubayo *et al*., 2010; Were *et al.,* 2013). The prevalent aphid species include *Myzus* *persicae, Macrosiphum euphorbia*, and *Aulocorthum solani.* One of the contributing factors to the extensive spread of the viruses is the presence of other weed host plants that harbour the viruses within or near the potato fields (Smith *et al*., 2012; Were *et al*., 2003). If effective virus management measures are not in place, the viruses tend to rapidly spread leading to crop losses (Frost *et al*., 2013; Khurana & Yadav, 2016).

Pests such as potato tuber moths, thrips, and leafminers are among the major biotic constraints that affect the potato quality and yields. The potato tuber moth (PTM), *Phthorimaea operculella,* is a widespread pest found across the globe and is among the significant potato damaging pests in the developing countries. *P. operculella* feeds on foliage by mining the potato leaves and stems and by attacking the tuber in the soil. When the foliage withers, the larvae move through soil cracks to reach the tubers, where they bore tunnels just beneath the skin. Initially, the larvae remain near the surface but later penetrate deeper into the tuber tissue. As they feed, they expel their excreta through the entry holes, leaving visible waste deposits on the tuber surface. The tuber develops a bitter taste making it unfavourable for human and livestock consumption (Otieno *et al.,* 2019).

Thrips, also known as *Frankliniella schultzei,* are common pests in Kenya. They suck the sap from the soft tissues of potato plants, causing the leaves to curl and eventually die when heavily attacked. In the temperate regions of Kenya, thrips are the major vectors of viral diseases. Similarly, leaf miners, such as *Liriomyza huidobrensis* are highly invasive pests and exhibit resistance to several insecticides (Reitz *et al*., 2013; Weintraub *et al.,* 2017). Adult leaf miners' feeds on the tissues of the leaf surface while larvae feed on the chloroplast-rich mesophyll, creating serpentine mines. This results in necrotic and brownish leaf tissue, giving the appearance of a burned crop field, especially in highly infested areas (Mugala *et al*., 2023). Chabi-Olaye (2008) reported that thrips infestation can reduce the ability of the leaves to carry out photosynthesis by up to 62% leading loss of yields.

### 2.2.2 Postharvest handling of potatoes

Postharvest management is an important factor in preserving nutritional value, safety and overall quality while preventing losses of potatoes. Most potatoes are exposed to unfavourable light, temperatures, and mechanical damage especially during harvesting, transportation and storage (Nema *et al.,* 2008). Most of the farmers harvest potatoes during sunny days and may leave them exposed for a long period which stimulates chlorophyll synthesis leading to 'greening' (Percival & Dixon, 2020). The mode of transport is vehicles and hand-pulled tracks with open backs which exposes the tubers to unfavourable conditions of sunlight and high temperatures (Musita *et al.,* 2019). Sometimes the potato tubers are stored for long periods of time under poor storage conditions of light and temperature (Nema *et al.,* 2008). During harvesting, transportation or storage, mechanical tissue damage or injury may occur (Wszelaczyńska *et al.,* 2020).

#### 2.2.2.1 Occurrence of glycoalkaloids in potatoes and their toxicity

Glycoalkaloids are poisonous secondary metabolites naturally produced by plants belonging to the Solanaceae family. Potatoes produce them during farming operations and postharvest handling processes (Omayio *et al*., 2016). Glycoalkaloids accumulate in potatoes during the exposure of the tubers to hostile conditions such as light, extreme temperatures, and bruising (Musita *et al.*, 2019; Nema *et al.*, 2008). The compounds are distributed throughout the potato plant (Nahar, 2011) with their highest concentration being in the skin of tubers, around the potato eyes, damaged areas and the sprouts (Nema *et al*., 2008).

**Table 2.1:** The levels of glycoalkaloids in various parts of the potato plant

| Plant Part | Glycoalkaloid content (mg/kg, fresh weight) |
|---|---|
| Sprouts | 2000-9970 |
| Bitter tasting tuber | 250-800 |
| Whole tuber | 10-150 |
| Peel (10-12%) | 150-1068 |
| Flesh | 12-100 |
| Leaves | 400-1000 |
| Stem | 30 |

**Source**: (Percival & Dixon, 2020)

The concentrations vary significantly depending on the genetic variety, maturity and exposure to unfavourable conditions of light and temperature, and stress factors. The predominant glycoalkaloids in potatoes are α-solanine and α-chaconine comprising about 95% of total glycoalkaloid content with α-chaconine being higher in concentration compared to α-solanine (Nema *et al.,* 2008). The rest (5%) including β- and γ- solanines, β- and γ-chaconine, α- and β-solamarines, and demissidine are present in very low amounts (Omayio *et al*., 2016).

The toxicity of glycoalkaloids is higher in man compared to animals Omayio *et al*., 2016). Their toxicity is as a result of anticholinesterase activity on the central nervous system which upsets the normal conduction of nerve impulses. They also disrupt cell membranes of the digestive system and other organs leading to gastrointestinal disturbances (Nema *et al*., 2008). Ingesting high doses of glycoalkaloids can lead to acute intoxication characterized by symptoms such as low blood pressure, neurological disorders, rapid pulse, and coma or death in extreme cases (Langkilde *et al*., 2009). Approximately, the toxic dose is estimated to be 2-5 mg per kilogram of body weight while the lethal dose is 3-6 mg per kilogram of body weight (Omayio *et al.,* 2016). Valcarcel *et al.* (2014) estimated a total daily intake of between 0.4 - 1.7 mg of glycoalkaloids per person per day based on the consumption of an estimated 158 g of potatoes per capita. Consistent potato products' consumers are exposed to cumulative safety risks in the long term. According to the Joint FAO/WHO Expert Committee on Food Additives (JECFA), total glycoalkaloid concentration below 100 mg per kilogram of potatoes fresh weight is considered non-hazardous to human health (JECFA, 1993).

### 2.3 Management of pests and diseases in potato farming

Pests and diseases' damage to potato crops curtails the maximum yield of potatoes leading to the reduction of the income of farmers (Okonya & Kroschel, 2015). To protect crops, farmers use pest management practices including the use of certified disease-free seeds, recommended spacing, fertilizer application, field hygiene, rotating crops with non-Solanaceous crops, weeding, irrigation, intercropping and pesticides use. However, pesticide use is the preferred management option for most farmers regardless of their potentially undesirable effects on the environment and human health (Mugambi *et al.*, 2021).

Pesticides are defined as any substance, or a mixture of substances of chemical or biological ingredients which are designed for repelling, destroying or controlling any pest, or regulating plant growth (FAO/WHO, 2014). They function by causing disturbance of the physiological activities of the organism targeted and eventually leads to dysfunction and reduced vitality (Taiwo, 2019). Pesticides are classified depending on how they are used but commonly the most appropriate method is categorizing them depending on chemical composition and description of the active ingredients. According to how they are used, pesticides are categorized into herbicides, insecticides, fungicides, nematicides, acaricides, molluscicides etc. Herbicides are the main category of pesticides used for eliminating weeds and other plants growing in unwanted areas while insecticides and fungicides are used to eliminate insects and fungi, respectively. Other categories such as acaricides, molluscicides and nematicides amongst others may be used on the soil to eradicate soil-borne pests or on the aerial part of the plant (Reis *et al*., 2020).

Pesticides are classified into four main categories based on their chemical composition: organochlorines, organophosphates, carbamates, and pyrethroids (Hassaan & El Nemr, 2020). Organochlorine insecticides, derived from chlorinated hydrocarbons have high toxicity, degrade slowly and tend to bioaccumulate in the environment. They take time to degrade with some persisting in the environment for 365 days and others up to 15 years (Hassaan & El Nemr, 2020). Some organochlorine insecticides such as dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH) have been banned in developed countries but continue to be used widely in developing nations despite their undesirable effects on the environment and humans. This is mainly because due to their low cost and strong effectiveness against a broad spectrum of pests (Jayaraj *et al*., 2016). However, the impact of their continued use on ecosystems and public health remain a significant concern, thus a great need for safer and more sustainable alternatives.

Organophosphates are organic ester derivatives of phosphorous, generally thiol or amide derivatives of thiophosphoric, phosphonic, and phosphoric acids with additional side chains of phenoxy, cyanide and thiocyanate groups. They function by inhibiting acetylcholinesterase enzyme (Omwenga *et al*., 2021). Since they are able to naturally degrade when exposed to air, sunlight, and soil, they are widely used as alternatives to organochlorines which are quite persistent in the environment. Also, they are water-soluble and get into the environment through dissolution, abrasion, and volatilization processes (Sidhu *et al.,* 2019). The most commonly used organophosphate insecticides include glyphosate, methyl parathion, malathion, chlorpyrifos, diazinon, quinalphos, endosulfan, profenofos, dimethoate, and monocrotophos (Mulla *et al*., 2020). These compounds have relatively short half-lives but are toxic to organisms that are not targeted and expose humans to risks. This raises concerns thus the need for responsible use and strict adherence to safety procedures.

Carbamates are esters derived from acids or dimethyl N-methyl carbamic acid, majorly used as herbicides, insecticides, or nematicides (Hassaan & El Nemr, 2020). These compounds function as the reversible inhibitors of the nervous system's enzyme acetylcholinesterase. They are effective against a wide range of insects, nematodes, molluscs and arachnids. They act as herbicides by blocking the electron transport pathway involved in photosynthesis. By binding spindle microtubules and blocking nuclear division blockade, they also function as fungicides (Mishra *et al.,* 2021). Among the mostly used carbamate pesticides are carbofuran, mancozeb, carbendazim, oxamyl, carbaryl, propoxur, phenmedipham, methomyl, aldicarb, and fenobucarb (Malhotra *et al.,* 2021). They are relatively unstable thus degrade within weeks or few months when in the environment. They are less persistent than organochlorines, but still raise environmental and health concerns due to their toxic nature. While their relatively shorter environmental persistence compared to organochlorines is an advantage, their impacts on non-target organisms and potential human exposure risks should be monitored carefully and alleviated.

Pyrethroids are synthetic insecticides obtained from pyrethrins which are natural compounds extracted from chrysanthemum flowers (Hassaan & El Nemr, 2020). They contain pyrethroid acids and keto-alcoholic esters of chrysanthemic compounds which are responsible for their insecticidal properties (Verma, 2021). Known for their rapid biodegradation, pyrethroids function by disrupting voltage-sensitive sodium channels (VSSC) in neurons, altering their excitability and paralysing the target organism (Molnar & Rakosy-Tican, 2021). Some of the commonly used pyrethroids include ɣ-cyhalothrin, pyrethroid, α-cypermethrin, and deltamethrin. Even though they rapidly degrade, pyrethroids still have environmental and health concerns. They adversely impact non-target organisms, bioaccumulate in the environment and pose health threats to exposed human beings. Pyrethroids thus require strict adherence to proper usage guidelines to mitigate potential negative effects. However, their rapid degradation and targeted mode of action make them a preferred choice over more persistent insecticides in certain applications (Shorokhov *et al*., 2021).

Pesticides being toxic substances require proper handling and application on crops due to the risks associated with their exposure (de Gomes *et al*., 2020). Poor handling of the pesticides can also result to increased resistance of pests and diseases to the chemicals, adverse health effects for farmers and consumers and environmental degradation. The effective use of pesticides is limited by factors such as insufficient knowledge among farmers thus the risk of food contamination. In some areas, farmers continue to use banned products, excessive application rates of chemicals, mixing multiple products containing different active ingredients and toxicity levels, and not complying with pre-harvest intervals (Oyoo *et al.,* 2021).

Focus on the responsible use of the registered products is enhanced to ensure adherence to specific instructions provided on the labels such as following correct rates and number of applications or sprays and ensuring that pre-harvest intervals are observed to avoid cases of exceedance of Maximum Residue Limits (MRLs). CropLife Kenya/Agrochemicals Association of Kenya trains farmers on adherence to label requirements, observance of Good Agricultural Practices (GAPs) and scouting for pests before spraying. The association also trains spray service providers who offer professional application of quality safe crop protection products to farmers. When pesticides are only handled by those who are trained, there is the assurance of better application of correct pesticides, at the correct time, and recommended rates and Pre-harvest intervals are observed at all times (AAK, 2022).

## 2.4 Regulation of pesticides in Kenya

In Kenya, the importation, exportation, manufacture, distribution, and pest control products use is regulated by the Pest Control Products Board (PCPB). This board was established under the Pest Control Products Act of 1982. It is illegal to import or sell any synthetic chemical products within the country without the PCPB approving. All approved products must be packaged and labelled as set out in the governing Act LN46/1984. The authority is in charge of regulating the final product, active ingredients' quality and modified or newly introduced compounds in the product. Also, it regulates chemical properties of a product containing these compounds, including additives like wetting agents and adjuvants.

The process of registering all the products starts when experimental labels and a copy of technical information are submitted to PCPB. The experimental trials for biological efficacy of the products are carried out by accredited institutions. Products that successfully pass these trials are supported by trial reports submitted to PCPB after which they receive a registration valid for three years renewable after every two years. The Pest Control Products (PCPs) are approved and authorized for use only after the applicant provides studies demonstrating that no significant residues can be found in the harvested produce after the specified Pre-harvest Interval (PHI) indicated on the label, as per the Pest Control Products Act of 1982. This rigorous process ensures that only safe and effective pesticides are introduced into the market, minimizing risks associated with human health, animal welfare, and environment (PCPB, 2005).

Furthermore, the PCPB is critical in monitoring the use of approved pesticides, enforcing compliance with regulations, and promoting safe handling practices among farmers and other stakeholders. Regular inspections, education campaigns, and collaboration with agricultural extension services help bridge the knowledge gap and encourage responsible pesticide use throughout the country. Currently, the PCPB is working on updating the legislation regulating products for controlling pests in the country. There is a revised proposed “Pest Control Products Bill, 2022” which is meant to strengthen protection of human and environmental health from the risks that arise after using synthetic products to control pests while encouraging Integrated Pest Management and Good Agricultural Practices (GAP).

**2.5 Pesticide residues in potato tubers and compliance with maximum residue levels**

Pesticide residue is defined as any specified substance present in or on food, agricultural commodities, or animal feed, as well as in environmental media such as water, resulting from the use of pesticides. This includes any pesticidal derivative, such as conversion and breakdown products, metabolites, reaction products, and impurities that are toxicologically or ecotoxicologically significant (FAO/WHO, 2014). For a product to be approved for use on a specific crop, the residues must be far below the safety levels for consumers and not exceed the Maximum Residue Levels (MRLs) that have been established. Some countries have set their own MRLs, while others use the Codex MRLs as the standard for trade.

After field application, some pesticides, due to their persistent nature remain in the ecosystem for an extended time and enter the food chain through multiple pathways (Ali *et al*., 2021; Xiao *et al*., 2021). Diffusion from the soil is the main way pesticides enter the potato tubers (Xiao *et al*., 2021). The amount of pesticide residues in the tubers depend on the number of applications, intervals, and rate of application on the agricultural field (Devi *et al*., 2018). In some instances, residue traces of pesticide or metabolites may be present in the crop even when pesticide use is per good agronomic practices (Leong *et al*., 2020).

Abd-Alrahman & Almaz (2012) observed that potato tubers harvested within five days of fungicide treatment had residue levels above the established MRLs. Frequently used pesticides such as glyphosate, chlorothalonil, mancozeb, chlorpyrifos, cymoxanil, profenofos, metamidophos, ɣ-cyhalothrin, thiamethoxam, propiconazole, pendimethalin, and carbofuran, pirimicarb, etoxazole, bifenthrin and paraquat residues' have been detected in potato tubers exceeding the MRLs (Juraske *et al*., 2011; Shalaby *et al*., 2021). Also, potato samples from local markets in Poland were reported to have concentrations of pesticides and their degradation products (thiamethoxam, ɣ-cyhalothrin, deltamethrin, rimsulfuron, and metalaxyl) above the MRLs established by European Union (Danek *et al*., 2021).

Good Agricultural Practices (GAPs) are key for ensuring that residual pesticide levels are below established MRLs by the time the crop reaches consumers at markets or retail outlets (FAO/WHO, 2019). In potato tubers, the MRLs are usually in the range of 0.01 to 10 mg/kg, which varies according to the active ingredient present in a pesticide. However, higher thresholds may be established in certain instances (Narenderan & Meyyanathan, 2019). Compliance with MRLs is very key for the health of consumers. Regulatory bodies therefore collaborate with stakeholders along the food value chain to enhance compliance with the set standards through regular inspections, education and enactment of best practices in pesticide management.

**2.6 Effects of pesticide residues on human health**

Pesticide residues when ingested in small amounts over extended period of time may cause chronic ailments and weakened immune system (Saraji *et al*., 2021). The residues accumulate in the bodies of consumers and cause serious health complications such as endocrine disruption, birth defects, genetic defects, cancers, neurotoxicity, and blood disorders (Devi *et al.,* 2018).

Exposure to glyphosate and other pesticides has been linked to the risk of tumour development (Kalyabina *et al.,* 2021). High concentrations of pesticide residues have been detected in fat samples of women with breast cancer in Malaysia. Also, chlorpyrifos has been shown to have the ability to disrupt redox balance thus altering the antioxidant defence mechanisms within cancer cells of the breast (Ventura *et al.,* 2015). Other research has also showed a positive link between exposure to pesticides and malignancies such as cancer of the prostate, lungs, pancreas, ovaries, testicles, liver, kidneys, intestines, brain tumours, and multiple myelomas (World Cancer Report, 2020). Evidence also suggests that prenatal exposure to pesticides is a major contributing factor to congenital malformations in newborns (Gerage *et al.,* 2017). Moreover, chronic neurological disorders have been linked to long-term exposure to organophosphate, organochlorine, and carbamate insecticides, as well as several fungicides (Khan & Rahman, 2017).

### 2.7 Effect of processing on pesticide residue concentration

Potatoes are processed to prolong shelf life, increase diversity, and improve flavour and quality of the nutrition. They undergo various processes, including washing, peeling, blanching, baking, frying, and other methods, which may lower levels of some of the pesticide residues (Liu *et al*., 2020; Yigit & Velioglu, 2020). The chemical properties of the pesticide residues and the conditions of the processing methods determine the extent of reduction of the pesticide residues. Pesticides with high solubility are eliminated easily using water than low-polarity pesticides (Yigit & Velioglu, 2020). Soliman (2001) reported a reduction in organochlorine and organophosphate pesticide residues by washing using acetic acid, tap water, and sodium chloride. During heat treatment pesticides undergo thermal degradation, evaporation and condensation (Naman *et al*., 2022). Frying has been reported to reduce organochlorines and organophosphates residues by 22.9 to 47.3% (Soliman, 2001). Microwave and oven-baking have been effective in reducing profenofos residues in fresh potatoes from 11.48 ppm to 0.22 and 0.19 ppm respectively. However, some processing methods have shown little or no impact on certain types of pesticides. During baking, there is no reduction in some pesticide residues such as thiabendazole (Padaliya *et al*., 2020). Some processing techniques cannot eliminate residues once they are in potatoes, thus the best course of action is to ensure good agricultural practices when applying pesticides to ensure low residues in tubers for the sake of consumer health.

### 2.8 Effect of processing methods on glycoalkaloid levels in potato tubers

Glycoalkaloids are water-soluble and highly heat-stable compounds. Temperatures of 210$^{o}$C for 10 minutes have been reported to reduce glycoalkaloid levels in potatoes by about 40% while the peeling process removes up to 60% of the total glycoalkaloids in potato tubers (Jayanty *et al*., 2019). Generally, potato glycoalkaloids remain stable under typical home cooking conditions, with only a slight reduction observed during boiling and baking (Uluwaduge, 2018). Boiling potato tubers in water leads to an average 22% reduction in their glycoalkaloid content due to solubility in water. Frying potatoes at temperatures of about 170°C results in a reduction of approximately 94% in glycoalkaloid levels (Pęksa *et al*., 2006).

## 2.9 Analytical methods for detection of pesticide residues

Usage of pesticides in agricultural production has been on the surge thus their residues require careful monitoring and control to protect the health of consumers. Pesticide residues are usually present in foods in small quantities. To ensure they are effectively and accurately quantified, their extraction and quantification is by the use of effective accurate, sensitive, and robust analytical methods and instruments (Sharma *et al.,* 2021; Wahab *et al*., 2022). There are different methods of extracting and detecting pesticides in foods that have been established, ranging from conventional extraction to sophisticated detection. Typically, pesticide residues analysis in foods involve extracting and cleaning the target analytes from the matrix and thereafter their quantification (Wahab *et al*., 2022).

### 2.9.1 Sample pretreatment and extraction methods

Sample pretreatment and extraction of the pesticides are very important steps in obtaining accurate quantitative results even though there has been advances that have led to development of very efficient analytical instrumentation (da Luz *et al*., 2017; Guo *et al*., 2018). The extraction process is a standardized approach that separates pesticide residues or the required analyte from the other sample matrix through use of a solvent without inducing any chemical changes in the pesticide (Wahab *et al*., 2022). Pesticide residues extraction from food matrices is dependent on the polarity of the pesticides and the type of food matrices involved, requiring appropriate sample pretreatment techniques so as to eliminate matrix interference (Min *et al.,* 2012). The solvent used in the process of extraction depends on the substrate and pesticide type. It should be highly soluble in the pesticides but have limited solubility for co-extractives. The solvents used mostly in various food matrices for pesticide residues analysis are methanol, acetonitrile, toluene, ethyl acetate, and dichloromethane. In some circumstances, solvents may be mixed to enhance the procedure recovery (Andrade *et al*., 2015; Boyati, 2021).

The extraction process begins by preparing sub-samples which involves cleaning and homogenizing 0.5 to 2 kgs of the initial materials. Extraction is performed on homogenized portions of 0.5 to 100 g. Various traditional methods such as liquid–liquid extraction, solid-phase extraction, matrix solid-phase dispersion, magnetic solid-phase extraction, supercritical fluid extraction, and solid-phase micro-extraction, gel permeation chromatography, dispersive solid-phase extraction, and liquid phase micro-extraction have been employed in the extraction of target pesticides from food matrices (Baganska *et al*., 2015; Meghesan-Breja *et al*., 2015; Narenderan *et al.,* 2019). However, these techniques are costly since they use large amounts of solvents, time-intensive, need advanced analytical equipment, and some have low recovery of analytes (Narenderan *et al*., 2019). Over the last decade, the Quick, easy, cheap, effective, rugged, and safe (QuEChERS) method has gained widespread use in pesticide residue extraction and multiresidue analysis because it is affordable, time saving, has less analysis stages, and high recovery of the analyte by using less volume of reagents (Rutkowska *et al*., 2018).

### 2.9.2 Quick, easy, cheap, effective, rugged, and safe method

The QuEChERS technique for preparation of samples in complex food matrices was developed by Anastassiades *et al*. (2003) and was named so because of the characteristics quick, easy, cheap, effective, rugged, and safe. Initially, it was developed for pesticide analysis in fruits and vegetables but adopted for pesticide extraction in different matrices with several studies reporting its use in the extraction of pesticide residues in potatoes (Reis *et al*., 2020), soils (Mungai & Wang, 2019) and water (Kamau, 2017). Due to its robustness, QuEChERS method has been endorsed by some regulatory bodies such as the Association of Official Analytical Chemists (AOAC 2007.01) and the European Standard (EN 15662) for compliance testing (Musarurwa *et al*., 2019). The core principles of the method are; liquid-liquid extraction, salting-out partitioning, and dispersive solid-phase extraction (d-SPE) cleanup using different types of sorbents. The extract obtained is thereafter injected into GC-MS or by LC-MS/MS for analysis after its diluted properly (Iqbal *et al*., 2020).

The QuEChERS technique is generally applied mainly using three standard procedures; the original (unbuffered) QuEChERS method, AOAC QuEChERS method and the buffered EN QuEChERS method. The unbuffered original QuEChERS method employs $MgSO_4$ and NaCl salts along with primary secondary amine sorbent at a concentration of 25 mg per millilitre of extract. In contrast, the EN method uses disodium citrate sesquihydrate buffer while AOAC uses the sodium acetate buffer. Also, during the dispersive solid-phase extraction step, the AOAC method uses 50 mg primary secondary amine per millilitre of extract while the EN method uses

25 mg primary secondary amine per millilitre of extract. In contrast, the EN method incorporates a disodium citrate sesquihydrate buffer, whereas the AOAC method uses a sodium acetate buffer (Musarurwa *et al*., 2019).

Buffers play a key role in cases of pH sensitive pesticides by ensuring better recovery for specific analytes (Reis *et al*., 2020). Salt combinations ($MgSO_4$ with NaCl) remain standard for phase separation, but also ammonium formate has been used to enhance compatibility with LC-MS/MS analysis, reducing ion suppression from matrix components (González-Curbelo, 2015). Dispersive-SPE cleanup is indispensable for reducing matrix effects in potato analysis. Potato tubers are rich in carbohydrates, glycoalkaloids and polyphenols, which can co-extract with target pesticides thus interfering with the detection (Reis *et al*., 2020). Interferences if present can hinder accurate pesticide identification and quantification as well as damage the analytical instruments. To prevent this, in the clean-up step, a sorbent is always used to adsorb the co-extracted materials from the matrix while retaining the target pesticide in the liquid phase. Various sorbents have been used successfully in pesticide residue analysis in food matrices using the QuEChERS technique. Some of the sorbents include, carbon-18, graphitized carbon black, zirconium-based sorbents, primary secondary amine, nanomaterial-enhanced sorbents (González-Curbelo, 2015; Lee *et al*., 2016; Malhat *et al*., 2017; Tette *et al*., 2016).

The QuEChERS method use for residue analysis in different matrices continue to increase (Narenderan & Meyyanathan, 2019). Recent advancements of the QuEChERS method are focused on enhancing selectivity, reducing matrix effects, and expanding analytical scope (Reis *et al*., 2020). The advancements target optimizing every step of the standard methods to fit various food matrices and target pesticides because the optimal parameters are different for each analyte and matrix (Nantia *et al*., 2017).

### 2.9.3 Chromatographic detection approaches

Pesticide residues in foods are usually present in very low concentrations. This necessitates the use of sensitive and selective techniques to quantify the compounds present in the sample extracts (Danek *et al*., 2021). The techniques used are; high-performance liquid chromatography (HPLC), gas chromatography (GC), or more exclusive approaches such as gas chromatography associated with mass spectrometry (GC-MS), ultra-high-performance liquid chromatography tandem mass spectrometry (UHPLC-MS/MS), and liquid chromatography associated with mass spectrometry (LC-MS). Currently, gas chromatography mass spectrometry

(GC-MS) and liquid chromatography–tandem mass spectrometry (LC-MS/MS) are the most common techniques for multi-residue pesticide analysis in food matrices due to their sensitivity, separation, and their capacity to identify compounds (Wahab *et al*., 2022).

#### 2.9.3.1 Gas chromatography - mass spectrometry

Gas chromatography mass spectrometry (GC-MS) is an analytical technique that separates chemical components through the gas chromatography (GC) component and subsequently identifies individual components at a molecular level via the mass spectrometry (MS) component (Ranjan *et al.,* 2023). It is suitable for analysing volatile, thermally stable organic compounds which is the characteristic of many pesticides (Pico *et al.,* 2020). The process begins by injecting the sample into the GC inlet, where it is vaporized and carried by an inert gas into a capillary column. This column, typically made of silica and coated internally with a stationary phase, enables the separation of compounds as they travel through it. The compounds in the sample separates as it moves along the column depending on their boiling point, interaction with the inner coating and the carrier gas. As a result, the compounds are retained for varying durations and elute at distinct retention times. Proper temperature control is essential for proper separation of the compounds. Temperature programming, involving either a continuous or stepwise increase in temperature, is commonly employed to optimize the process (Chevalier & Sommerer, 2011).

After leaving the column, the compounds enter the mass spectrometry instruments. At the ion source, the sample molecules collide with electrons (70eV) and form molecular ions and smaller ions with characteristic relative abundances. The ions are propelled into the mass analyzer, where they are sorted depending on their mass-to-charge ratio (m/z). Once separated, the detector counts the ions and produces an electrical signal, resulting in a mass spectrum that displays relative ion intensity versus m/z values (Garg & Zubair, 2024). The ion with the greatest intensity is designated as the base peak (100%), while the intensities of other ion peaks are expressed relative to this base peak (Skoog et al., 2018).

Various types of mass spectrometers may be necessary depending on the sensitivity and selectivity needed. The most commonly used detector is the flame ionization detector (FID). Flame photometric detectors (FPD), electron capturing detectors (ECD), nitrogen phosphorus detectors (NPD), and mass selective detectors (MSD) are also used. Mass spectrometer detectors

(MS and tandem MS) can also be used during pesticides residue analysis (Wahab *et al*.,2022). When gas chromatography (GC) is combined with a mass spectrometer (MS) that uses a single quadrupole analyzer, the system is referred to as GC–MS. This method is widely utilized in routine sample analysis, whether targeted or untargeted, through approaches such as selected ion monitoring (SIM) for targeted analysis or full scan acquisition for untargeted analysis (Hernández-Mesa & Moreno-González, 2022). When gas chromatography is combined with a triple quadrupole mass spectrometry, the system is termed GC-MS/MS. The triple quadrupole MS is the most suitable for scenarios that require high selectivity and operates in a selective reaction monitoring (SRM) mode. The high selectivity is important in minimizing background ion interferences and generating a high signal-to-noise ratio, enhancing the detection of desired compounds (Vazquez-Roig & Pico, 2012). Moreover, integrating a GC system with a high-resolution accurate mass (HRAM) spectrometer combines the quantitative performance of a triple quadrupole GC-MS/MS with the precise full-scan HRAM functionality of highly sensitive and accurate mass spectrometers. These systems are particularly well-suited for applications requiring precise identification of both targeted and unknown compounds (Pico *et al.,* 2020).

#### 2.9.3.2 Liquid chromatography-tandem mass spectrometry

LC–MS/MS is an analytical method that integrates the separation efficiency of liquid chromatography (LC) with the detection and identification precision of mass spectrometry (MS) (Ng et al., 2024). Mostly it is employed during the analyses of non-volatile and thermolabile polar compounds that are non-GC amenable (Raina, 2011). LC-MS/MS is used to analyse several pesticides from various chemical classes in food matrixes that are very complex in a single run due to its high sensitivity and selectivity. This requires parameter optimization specific for each compound and thus is unsuitable for screening untargeted compounds (Masiá *et al*., 2016).

A standard LC–MS/MS setup includes several key components: a high-performance liquid chromatography (HPLC) system, an atmospheric pressure ionization (API) source, a vacuum unit, a mass analyzer, a detector, and a computer for instrument control and data interpretation. Within the HPLC column, the sample components are separated based on how differently they interact with the stationary phase. Substances that bind more strongly to this phase move more slowly, leading to separation determined by properties such as molecular size, polarity, and charge (Chauhan & Kumbhar, 2025). After separation, the API unit converts the eluted compounds into gas-phase ions, while the mobile phase is directed to waste. These ions are then sorted by their mass-to-charge (m/z) ratio in the mass analyzer, and the detector measures the ions, generating signals that are processed by the computer to produce a mass spectrum. The analysis and detection of the mass take place under vacuum conditions (Corradini, 2011).

**2.10 Analytical methods for detection of glycoalkaloids in potatoes**

The detection and quantification of glycoalkaloids is key in ensuring compliance with regulatory limits of 200 mg/kg fresh weight. Analytical methodologies rely on chromatographic techniques coupled with mass spectrometry, alongside traditional high-performance liquid chromatography (HPLC) with ultraviolet or diode array detectors to detect glycoalkaloids (Singh & Raigond, 2020).

Liquid chromatography tandem mass spectrometry has emerged as a sensitive, selective, and rapid method for targeted quantification of potato glycoalkaloids. These methods typically begin with extraction (e.g., aqueous acetic acid) and clean-up via solid-phase extraction (SPE) before separation using reversed-phase HPLC and electrospray ionization mass spectrometry in single-ion monitoring or multiple reaction monitoring modes. Detection limits often reach single-digit µg/kg, enabling high-throughput screening with minimal interference from complex matrices (Matsuda *et al*., 2004). For instance, Wan *et al*. (2022) introduced an innovative electro-membrane extraction combined with LC-MS/MS, which allowed selective enrichment of steroidal glycoalkaloids from potato tissues and enhanced matrix cleanup capability.

UHPLC-HRMS and Orbitrap-based methods are increasingly employed in metabolomics studies due to their ability to screen for both known and unknown glycoalkaloids. Utilizing high-resolution accurate mass data and full-scan acquisition, these approaches enable comprehensive profiling of glycoalkaloid concentration and distribution in potato tubers, sometimes extending to environmental stress or storage investigations. For example, high-resolution mass spectrometry imaging (MALDI-TOF MSI) has been used to map glycoalkaloid spatial distribution across potato tissues during storage, revealing that concentration peaks in periderm and sprouts over time (Yeng *et al*., 2020).

While colorimetric, gravimetric, and thin layer chromatography-based assays are largely obsolete, having been replaced due to their poor specificity, limited sensitivity, and inability to distinguish individual individual glycoalkaloids, they still provide a historical baseline (EFSA, 2020). High-performance liquid chromatography Diode Array Detection (HPLC DAD) remains relevant, particularly in resource-limited settings.

# CHAPTER THREE
# MATERIALS AND METHODS

## 3.1 Study site

A preliminary survey was conducted in Nyandarua County among farmers and traders along the potato value chain. Nyandarua County lies between 0° 32' 59.99" N and 36° 36' 59.99" (Figure 1). Nyandarua County has an area of approximately 3,286 km² with a population of 638,289. The weather pattern is predictable and temperatures range is 12°C (June and July) and 25°C (January and February). Annually, the rainfall is usually between 700 mm and 1,500 mm. There are six constituencies in the county: Ol-Kalou, North Kinangop, Ol-Joro-Orok, South Kinangop, Ndaragwa and Kipipiri. The major economic engagement in the county is farming. The local economy primarily relies on dairy farming and production of crops such as potatoes, vegetables, maize, wheat and beans. Nyandarua County is the top producer of potatoes nationally and contributes about 33% of the total potatoes with an annual production of 550,000 tonnes (National Potato Council of Kenya, 2017).

Raw potato *(Solanum tuberosum* L.) tubers (*Shangi* variety) for use in the study were obtained from the traders and farmers in Ol-Kalou, North Kinangop, Ol-Joro-Orok, South Kinangop, Ndaragwa and Kipipiri sub-counties. Processing of the tubers was done at the food pilot plant in the Dairy and Food Science and Technology, Egerton University. Experimental analyses were conducted at the Jomo Kenyatta University of Agriculture and Technology (JKUAT) analytical chemistry laboratory and Egerton University animal science laboratory.

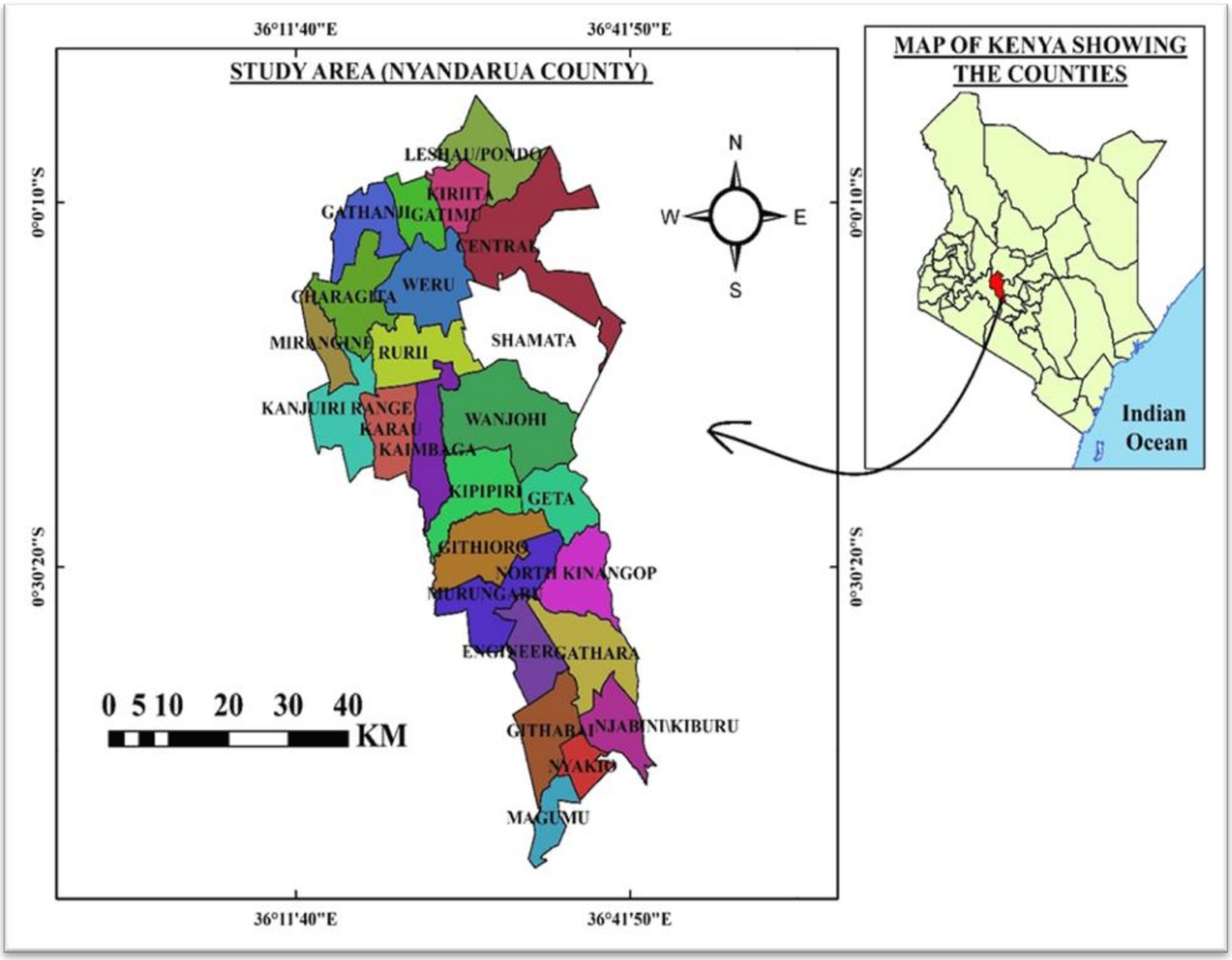


**Figure 3.1:** The map of Nyandarua County

### 3.2 Evaluating handling practices along the potato value chain in Nyandarua County

#### 3.2.1 Study type and design

This study employed a cross-sectional approach using qualitative data collection techniques such as semi-structured questionnaires and observations.

#### 3.2.2 Sampling procedure

This study involved a multistage cross-sectional survey to assess on-farm pesticide practices among smallholder potato farmers (farming in less than 2 hectares of land) in Nyandarua County. Two wards with the highest production of potatoes within each sub-county were purposively selected for the study. Within the wards, farmers who had engaged in potato production for a minimum of two seasons were randomly chosen to participate in the study. Potato farmers (n=275) selected were interviewed using semi-structured questionnaires. The questionnaire was divided into four sections: introduction, demographic data, experience in potato farming, potato pesticide management **(Appendix 2).**

For postharvest handling practices, the study population consisted of all the value chain actors (farmers and traders). The technique used to get the actors to participate in the study was simple random sampling. The questionnaires were administered to randomly selected potato farmers and other handlers (n=110) along the value chain. The questionnaire was divided into three sections: introduction, demographic data, postharvest handling and storage **(Appendix 3)**.

### 3.2.3 Sample size

For on-farm pesticide practices, the Cochran equation was used to determine the sample size of respondents (Nanjundeswaraswamy & Divakar, 2021).

$$n_o = (Z^2 \times p \times q)/e^2$$

where;

$n_o$ represents the desired sample size if the target population is more than 10,000

Z represents the standard deviation at the required confidence level of 1.96 (Z value found in Z table)

e represents the desired level of precision (margin of error) i.e., level of statistical significance set, ±5% (0.05)

p represents the estimated proportion of the population desired (0.8)

q represents 1-p (proportion expected not to have the features under study) = (1-0.8) = 0.2

Using the formula;

$$n_o = (Z^2 \times p \times q)/e^2$$

$$= (1.96^2 \times 0.8 \times 0.2)/0.05^2$$ =246 respondents.

Approximately 250 respondents. Taking into account a 10% attrition rate (10% of 250=25), the sample size was adjusted to (250+25) =275 respondents.

For postharvest handling practices, the sample size was calculated using the Fisher formula (Muyembe & Anselemo, 2023).

$$n = \frac{z^2 * p * q}{d^2}$$

Where;

n is the minimum sample size required

Z represents the standard deviation at the required confidence level of 1.96/95% confidence interval (Z value found in Z table)

p represents the estimated proportion of the population expected to have the characteristics under study; in this case, those selling potatoes (50%) =0.5

q. proportion not expected to have the characteristics under study (1-p) =0.5

d represents the desired level of precision (margin of error) i.e., level of statistical significance set, ±10% (0.1)

Using the formula; $n = \frac{z^2 * p * q}{d^2}$

$= (1.96^2 \times 0.5 \times 0.5)/0.1^2$ =96 respondents.

Approximately 96 respondents. Taking into account a 10% attrition rate (10% of 100=10), the sample size was adjusted to (100+10) = 110 respondents.

### 3.2.4 Survey instrument

Data collection was done using a semi-structured questionnaire. It was written in English and uploaded on an open data kit (ODK). It captured socio-demographic information of respondents, and information on the knowledge of pesticides and practices **(Appendix 2).** Potato post-harvest handling practices such as exposure to sunlight, storage, the mode of transportation, exposure to mechanical injuries, and any other relevant information were also collected using the tool and through observations **(Appendix 3).** The tool was pretested on randomly picked thirty farmers within Nyandarua County, Kenya and the feedback used to refine the instrument to ensure it was suitable for the target population.

### 3.2.5 Study ethics

Before the administration of the questionnaires, information about the intent of the study was communicated to the respondents. They were notified that information they would provide was purposefully for the study and was not to be shared with third parties or be used for any political activity. Confidentiality of their information was assured and were requested to consent that they have accepted to voluntarily participate in the study **(Appendix 1).**

### 3.2.6 Data analysis

Responses were uploaded onto the open data kit application and then sent to a cloud-based server. Thereafter, the data was transferred to Microsoft Excel. After cleaning the data, 250 responses were used in data analysis for pesticide practices and 100 responses for post-harvest handling practices. The data was then exported to Statistical Package for Social Science version 21 (SPSS) software for analysis. Descriptive statistics namely, percentages and frequencies were used to express the results of socio-demographic characteristics of the study population and the different on-farm pesticide practices and post-harvest handling practices.

## 3.3 To determine the effect of the handling practices on pesticide residue and glycoalkaloid levels in potato tubers

### 3.3.1 Collection of potato samples

Samples of potato tubers for pesticides residue analyses were collected from all the respondents. Samples collected from farmers with similar practices were grouped into a single treatment category. In total, there were sixteen distinct categories based on shared practices as shown in Table 3.1. The samples were stored at 4°C and taken to the laboratory for analysis on the next day.

**Table 3.1:** Categories of on-farm pesticide application practices

| Category of practice | Practice |
|---|---|
| Mixing pesticides | Mixing of fungicide and foliar liquid fertilizer |
| | Mixing of fungicide and insecticide |
| | Don’t mix pesticides |
| Application rates/dosage of pesticides source of instruction | Follow the manufacturer’s instructions |
| | Asks from the agro vet |

| | |
|---|---|
| | Asks from other farmers |
| Frequency of application | Every 7 days |
| | Every two weeks |
| | Three times a month |
| | Spray when the farm is attacked by pests and diseases |
| Timing | Before planting |
| | During emergence |
| | During tuber development |
| Pre-harvest interval | 3 weeks |
| | 4 weeks |
| | 5 to 6 weeks |

Potato tubers for glycoalkaloid levels determination were sampled from the farmers and traders. Samples were grouped into four categories; exposed to light/greened, sprouted, mechanically injured/bruised and fresh tubers.

### 3.3.2 Determination of pesticide residue levels in potato tubers

The separation and quantification of the target pesticides (imidacloprid, fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, 2,4-D, atrazine, metolachlor, glyphosate, azoxystrobin, mancozeb, metalaxyl) was done by gas chromatography-mass spectroscopy (GC-MS, Shimadzu GCMS-QP 2010 SE) and liquid chromatography-tandem mass spectrometry (LC-MS/MS, Agilent Technologies 1100 Series) system connected to a Waters Quattro-ultima mass spectrometer. The system was operated and managed using Waters MassLynx software.

#### 3.3.2.1 Pesticide standards preparation

The pesticide reference standards (purity ≥98.5%) (imidacloprid, fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, 2,4-D, atrazine, metolachlor, glyphosate, azoxystrobin, mancozeb, metalaxyl, deltamethrin) were purchased from Sigma-Aldrich, Germany through Kobian Scientific (Kenya). For each pesticide, stock solution at a concentration of 1 mg/mL was prepared in HPLC-grade methanol and stored at -20°C. Two sets of Intermediate Mixed Standard (IMS) were prepared: one containing imidacloprid, 2,4-D, atrazine, glyphosate, azoxystrobin, mancozeb, and metalaxyl for LC-MS/MS analysis, and the other containing fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, deltamethrin, and metolachlor for GC-MS analysis. Working standards for daily analysis were prepared by diluting the IMS in methanol.

#### 3.3.2.2 Reagent blanks and matrix blanks

Reagents used in the extraction of pesticide residues (15 ml of 1% acetic acid in acetonitrile, 1.5 g anhydrous sodium acetate, and 6 g anhydrous magnesium sulfate) without the sample matrix were prepared. Matrix blanks were prepared using pesticide-free potato tubers. Extraction of the reagent and matrix blanks was by use of the "Quick Easy, Effective, Rugged and Safe" (QuEChERS) multi-residue method.

#### 3.3.2.3 Method validation

The performance of the method was validated based on selectivity, linearity, precision, recovery, limit of detection (LOD) and limit of quantification (LOQ). Selectivity was assessed by analyzing reagent blanks and matrix blanks. Analysis of six replicate reagents and matrix blanks was done and any interfering compounds were examined in the resulting chromatograms within the expected retention times of the target analytes in the samples.

The linear range of the analytical techniques was examined using calibration curves. To create calibration curves, standards with varying concentrations were injected in triplicate: 0 μg/L, 10 μg/L, 20 μg/L, 50 μg/L, 100 μg/L, 200 μg/L, 400 μg/L, and 600 μg/L for LC-MS/MS analysis, and 0 μg/L, 200 μg/L, 400 μg/L, 500 μg/L, 600 μg/L, 1000 μg/L, and 2000 μg/L for GC-MS analysis.

Precision was calculated as the percentage relative standard deviation for each spiking concentration level. Potato blank samples were spiked with pesticide standards at three concentration levels; 10, 50, and 100 μg/L for imidacloprid, 2,4-D, atrazine, glyphosate, azoxystrobin, mancozeb, and metalaxyl; and 200, 500, and 1000 μg/L for fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, deltamethrin, and metolachlor. Two replicates were analyzed for each concentration level. The percentage relative standard deviation was calculated by dividing the standard deviation of the results by the mean and multiplying by 100 for each level**.**

Recovery was determined by comparing the concentrations of samples before and after spiking. A total of 15 g of the blended blank samples were spiked with the standard stock solution for imidacloprid, 2,4-D, atrazine, glyphosate, azoxystrobin, mancozeb, and metalaxyl at a concentration of 10, 50, and 100 μg/L, and a concentration of 200 μg/L, 500 μg/L and 1000 μg/L for fenitrothion, chlorpyrifos, α-cypermethrin, lambda-cyhalothrin, deltamethrin, and metolachlor. The spiked samples were left to stand for ten minutes, then concentrations were determined in duplicate before and after extraction using QuEChERS multi-residue method.

For every compound, the limit of detection (LOD) and limit of quantification (LOQ) determined using the criterion that the LOD is the analyte concentration that gives a signal-to-noise ratio of 3, while the LOQ is the analyte concentration that gives a signal-to-noise ratio of 10.

### 3.3.2.4 Sample preparation, pesticide extraction, clean-up and analysis

Raw potato tubers, approximately 0.5-2 kg from each labelled sample, were washed under running water, peeled, and chopped. The samples were homogenized in a blender for 1 minute. This was done in duplicate for every sample. Pesticide residues were extracted and cleaned up using the QuEChERS method, which is the modified AOAC official method 2007.1 (AOAC, 2007). An amount (15 g) of each homogenized portion was weighed into a polypropylene centrifuge tube of size 50 ml. Extraction was performed by adding 15 ml of 1% acetic acid in acetonitrile (prepared on a v/v basis, 10 mL glacial HOAc in a 1 L MeCN solution), 1.5 g anhydrous sodium acetate, and 6 g anhydrous magnesium sulfate ($MgSO_4$) to the weighed sample followed by mixing in a vortex mixer (Digisystem vortex mixer) for 1 minute then centrifugation at 5000 rpm for 1 minute (Thermofisher Scientific Centrifuge). After centrifugation, the supernatant (5 ml) was transferred to another centrifuge tube. Then, 150 mg of $MgSO_4$ and 50 mg of primary-secondary amine (PSA) were added and mixed for 30 seconds. Centrifugation was then done at 5000 rpm for 1 minute.

A millilitre aliquot of each sample was transferred to a centrifuge tube and subjected to nitrogen gas evaporation at 50°C for 25 minutes to concentrate the sample. Then, the dried residue was re-dissolved using either 1 ml of methanol (for GC-MS analysis) or 1 ml of 10% acetonitrile solution (for LC-MS/MS detection). The solutions were filtered through 0.2 μm polyethersulfone syringe filters directly into the chromatography vials for the mass spectrometry systems. This was done in duplicate. The cleaning procedure between trials was automated to prevent carryover and ensure accurate results.

### 3.3.2.5 Liquid chromatography-tandem mass spectrometry system optimal conditions

LC-MS/MS screening was achieved using liquid chromatography (Agilent Technologies 1100 Series) coupled to a triple quadrupole mass detector. The mass spectrometer was operated in electrospray ionisation (ESI) using positive and negative ion modes. The positive ion mode was used for the analysis of atrazine, imidacloprid, mancozeb, and metalaxyl, while the negative ion mode was used for 2,4-D, glyphosate, and azoxystrobin. The capillary voltage was set at 3.0 kV, source temperature at 100°C, desolvation temperature at 350°C, and desolvation gas flow rate at 700 L/hr. Nitrogen gas was used for desolvation while argon gas was utilized as a collision gas. Separation was carried out using a Kinetex EVO C18 column (100 mm x 3.0 mm, 5µm particle size, 100 Å). Deionised water containing 0.1% formic acid (mobile phase A) and acetonitrile and deionised water (95:5, V/V) containing 0.1% formic acid (mobile phase B) were used for the gradient program, which began with 10% B for 3 minutes and linearly increased to 90% after 15 minutes. The column was reprogrammed for 20 minutes to return to 10% B. The column temperature was maintained at 35 ºC. The injection volume was 10µL with a flow rate of 0.45 µL/minute.

### 3.3.2.6 Gas chromatography-mass spectroscopy optimal conditions

The GC-MS (Shimadzu GC-MS-QP 2010 SE) coupled with a 5975 inert Mass Selective Detector (MS) and containing a DB-5ms column (length: 30 m, ID: 0.25 mm, film thickness 0.25 µm) was used. Sample injection was achieved in a split-less mode with an injector and interface temperature of 250°C. The carrier gas with a flow rate of 1.2 ml/min under an injection port temperature of 280°C was helium gas. Electron ionization was at –70 eV under an ion source temperature of 240°C, and full-scan modes between 50 m/z and 500 m/z for the detection of different analytes. The source and the interface temperatures were held constant at 200°C and 250°C respectively. The oven temperature program began at 50°C and was held for 1 minutes, followed by an increase to 150°C at a rate of 25°C per minute. Finally, the temperature was ramped up to 250°C at a rate of 10°C per minute. This temperature program resulted in a total run time of 25 minutes, enabling complete separation of all the analyzed compounds.

#### 3.3.2.7 Quantification of pesticide residues

Quantification was performed using the external calibration curves prepared from standard solutions in methanol. Matrix blanks and spike recovery studies were used to evaluate potential matrix effects, ensuring reliable results.

### 3.3.3 Determination of glycoalkaloid levels

The levels of glycoalkaloids were determined using high-performance liquid chromatography (HPLC, Agilent Technologies 1100 Series) equipped with a photodiode array detector set at a wavelength of 202 nm as described by Musita *et al*. (2019). The separation was achieved using stainless steel LC column (250 ×4.6 mm) packed with Hypersil ODS 5 µm particle size fitted into the HPLC equipment. The operating conditions: a flow rate of 1.5 ml/min, injection volume of 50 µl, a run time of 15 minutes, column temperature of 40°C, and wavelength detection set at 202 nm using a Diode Array Detector (DAD).

#### 3.3.3.1 α-solanine and α-chaconine standards preparation

The glycoalkaloids reference standards α-solanine and α-chaconine (purity ≥ 99.5%) were purchased from Sigma-Aldrich, Germany through Kobian Scientific (Kenya). Stock solutions for individual pesticides at a concentration of 1 mg/ml were prepared in HPLC-grade methanol and stored at -20°C. Mixed stock solutions were diluted daily with the mobile phase to concentrations of 2 to and 100 µg/L (2, 5, 10, 20, 50, and 100 µg/L) as the working solutions. All standards and stock solutions were stored at -20°C in the dark, and the working solutions were stored at 4°C in the dark before use. Calibration curves were prepared by injecting a series of standards for HPLC analysis. Recovery was determined by comparing the concentrations of samples before and after spiking.

#### 3.3.3.2 Sample preparation for glycoalkaloids extraction

A weight of 0.5-2 kgs of potatoes from each labelled sample from various actors along the value chain were washed under running water, peeled, chopped, and blended.

#### 3.3.3.3 Drying of potato tubers

Different potato samples were oven dried as described by AOAC (2005) method number 930.15. Dried tuber powder (3 grams) was weighed accurately in triplicate using an analytical balance. The weighed samples were dried in an oven (type SO, FNr 862187, Schwabach W-Germany) at 105ºC for 1 hour. The dried samples were then placed in a desiccator to cool.

#### 3.3.3.4 Extraction of glycoalkaloids

Two grams of the dried sample were mixed with 20 ml extraction solution comprising of water, acetic acid, and sodium hydrogen bisulfite (100 + 5 + 0.5, v/v/w) and shaken for 15 minutes with a Burrell vertical shaker. Clarification of the mixture was then done by centrifugation (HERMLE Labnet, model Z382K, Germany) for 30 min at 800×g as described by Musita *et al*. (2019).

#### 3.3.3.5 Cleaning of the extract, analysis and quantification

Solid Phase Extraction (SPE) columns were conditioned using five millilitres of acetonitrile followed by a 5 ml extraction solution composed of water, acetic acid, and sodium hydrogen bisulfite (100 + 5 + 0.5, v/v/w). At a controlled pressure, a volume of 10 ml of the supernatants was passed through the SPE columns and then 4 ml wash solution (15% acetonitrile) was used to wash glycoalkaloids. Elution with a 4 ml LC mobile phase (60% acetonitrile in 0.01 M phosphate buffer) at a rate of 1–2 drop/s was done. The final volume collected was adjusted to 5 ml with LC mobile phase, filtered through a 0.45 µm membrane, transferred into vials and stored frozen until injection for analysis.

External calibration curves prepared from the standard stock solutions were used to quantify glycoalkaloids. The concentration levels were expressed as mg glycoalkaloids per kilogram on a dry weight basis.

### 3.3.4 Statistical Model

The experiment employed a Completely Randomized Design (CRD) with each practice identified as a treatment.

Response variables were pesticide residues and glycoalkaloid levels.

Statistical model;

$$\mathbf{Y_{ijk} = \mu + \tau_i + \varepsilon_{ijk}}$$

where;

$\mathbf{Y_{ijk}}$ was the pesticide residue/glycoalkaloid level

$\boldsymbol{\mu}$ was the overall mean of the pesticide/ glycoalkaloid level

$\boldsymbol{\tau_i}$ was the effect due to the i$^{th}$ practice

$\boldsymbol{\varepsilon_{ijk}}$ the random error associated with $\mathbf{Y_{ijk}}$.

### 3.3.5 Data analysis

All analyses were performed in triplicate using the PROC GLM procedure of the Statistical Analysis System (SAS Institute Inc., 2006) software Version 9.4. The study hypotheses were tested using Analysis of variance (ANOVA). The level of statistical significance was established at a confidence level of $P < 0.05$, and means separation was done using Tukey's Honestly Significant Difference (HSD) method.

## 3.4 The effect of common processing methods on the pesticide residues and glycoalkaloid levels in potato products

The study examined how pesticide residues and glycoalkaloid levels in potato tubers are affected by common processing methods. Six kilograms of raw potato samples containing known levels of multiple pesticide residues 2-4, D (9.39 µg/kg), atrazine (1.86 µg/kg), metalochlor (3.8 µg/kg), glyphosate (4.63 µg/kg), mancozeb (22.81 µg/kg), metalaxyl (15.46 µg/kg), imidacloprid (3.33 µg/kg), fenitrothion (25.32 µg/kg), chlopyrifos (24.65 µg/kg), α-cypermethrin (22.36 µg/kg) and γ-cyhalothrin (12.17 µg/kg) were processed as described in section 3.4.1. Similarly, six kilograms of raw potato tubers containing known levels of α-chaconine (200.4 mg/kg) and α-solanine (129.38 mg/kg) were processed as described in section 3.4.1.

### 3.4.1 Common processing methods of potatoes

The common methods used in potato processing are described in Table 3.2.

**Table 3.2:** Common processing methods of potatoes

| Method | Processing conditions | Reference |
|---|---|---|
| Roasting | 500 g of peeled potatoes was placed onto a heated oven tray and | Skog *et al.*, |

| | | |
|---|---|---|
| | maintained at 130°C for 15 minutes. | 2008 |
| Boiling | 500 g of peeled potatoes were suspended in boiling water for 30 minutes. The ratio of potato pieces to water was 1:4 (w/v). | Jayanty *et al*., 2019 |
| Steaming | 500 g of peeled potatoes were put into a strainer at a depth of about 2 cm for homogeneity in the heat-steaming process and steam-treated for 20 minutes. | Cheigh *et al*., 2012 |
| Frying | 500 g of peeled potatoes, sliced to a uniform thickness (6×2×1 cm) by a mechanical slicer, were completely immersed in sunflower oil (5 litres preheated for 1 hour before frying), contained in an electrical fryer set at 180°C for 3 minutes. | Jayanty *et al*., 2019 |
| Baking | 500 g of peeled potatoes, sliced to a uniform thickness (6×2×1 cm) by a mechanical slicer, were coated with sunflower oil and placed on a stainless-steel wire mesh inside the oven set at 170°C for 20 minutes. | Jayanty *et al*., 2019 |

### 3.4.2 Pesticide residues and glycoalkaloids level determination

After processing, the samples cooled to room temperature and thereafter, pesticide residue and glycoalkaloid levels were determined as described in sections 3.3.2 and 3.3.3, respectively.

### 3.4.3 Experimental design

The experiment employed a Completely Randomised Design (CRD) with processing methods (roasting, baking, boiling, frying and steaming) as treatments. Response variables were pesticide residues and glycoalkaloid levels.

Statistical model;

$$\mathbf{Y_{ijk} = \mu + \tau_i + \varepsilon_{ijk}}$$

where;

$\mathbf{Y_{ijk}}$ is the pesticide residue/glycoalkaloid level

$\boldsymbol{\mu}$ is the overall mean of the pesticide/ glycoalkaloid level

$\boldsymbol{\tau_i}$ is the effect due to the $i^{th}$ processing method

$\boldsymbol{\varepsilon_{ijk}}$ is the random error associated with $\mathbf{Y_{ijk}}$.

### 3.4.4 Data analysis

All analyses were performed in triplicate using the PROC GLM procedure of the Statistical Analysis System (SAS Institute Inc., 2006) software Version 9.4. The study hypotheses were tested using Analysis of variance (ANOVA). The level of statistical significance was established at a confidence level of $P < 0.05$, and means separation was done using Tukey's Honestly Significant Difference (HSD) method.

# CHAPTER FOUR
# RESULTS

The findings of the first objective detail the handling practices by farmers, and traders along the potato value chain in Nyandarua County. The glycoalkaloids and pesticide residue levels in potato tubers as influenced by handling practices are presented as part of the second objective. The findings on how various processing techniques affected the levels of glycoalkaloids and pesticide residues in potato products which are the results for objective three are also provided in this chapter.

## 4.1 Socio-demographic characteristics of potato farmers

Table 4.1 shows the socio-demographic data of potato farmers in Nyandarua County. More than half (54.4%) of the respondents were male. The majority (80.4%) were aged 40 years and above, while 19.6% were below 40 years old. Most of the respondents (87.5%) had received formal education. In terms of experience in potato farming, 47.6% had over five years of experience while 52.4% had less than five years.

**Table 4.1:** Socio-demographic characteristics of potato farmers in Nyandarua County

| Characteristic | Variable | Frequency (n=250) | Percentage (%) |
|---|---|---|---|
| Gender of the farmer | Male | 136 | 54.4 |
| | Female | 114 | 45.6 |
| Age of the farmer | 18-29 | 5 | 2 |
| | 30-39 | 44 | 17.6 |
| | 40-49 | 76 | 30.4 |
| | 50-59 | 91 | 36.4 |
| | 60-69 | 27 | 10.8 |
| | >70 | 7 | 2.8 |
| Level of education | never attended | 31 | 12.4 |
| | Didn't complete primary | 46 | 18.4 |
| | Completed Primary | 49 | 19.6 |
| | Didn't complete secondary | 44 | 17.6 |
| | Completed Secondary | 47 | 18.8 |
| | Tertiary level | 33 | 13.2 |

| | | | |
|---|---|---|---|
| Years in potato farming | less than a year | 2 | 0.8 |
| | two years | 17 | 6.8 |
| | three years | 32 | 12.8 |
| | four years | 36 | 14.4 |
| | five years | 44 | 17.6 |
| | more than five years | 119 | 47.6 |

**4.2 Socio-demographic characteristics of the potato traders**

As illustrated in Table 4.2, female respondents were the majority (64%). Respondents within the 50-59 years age group were the majority (35%) while those within the youngest age group (18-29 years) were the least (3%). The majority of the respondents (37%) did not complete primary education, while only 2% had attained tertiary education.

**Table 4.2:** Socio-demographic characteristics of the traders

| Socio-demographic Characteristics | Variable | Frequency (n=100) | Percentage (%) |
|---|---|---|---|
| Gender | Male | 36 | 36 |
| | Female | 64 | 64 |
| Age of the farmer | 18-29 | 3 | 3 |
| | 30-39 | 14 | 14 |
| | 40-49 | 26 | 26 |
| | 50-59 | 35 | 35 |
| | >60 | 22 | 22 |
| Level of education | never attended | 2 | 2 |
| | Didn't complete primary education | 37 | 37 |
| | Completed primary education | 31 | 31 |
| | Didn't complete secondary education | 23 | 23 |
| | Complete secondary education | 5 | 5 |

| | | | |
|---|---|---|---|
| | Tertiary education | 2 | 2 |

**4.3 Pesticides commonly used in potato production**

The type of pesticides commonly applied in *Shangi* potato variety production in Nyandarua County are presented in Figure 4.1. The majority of the farmers (98.8%) rely on synthetic pesticides to control pests and diseases on their farms. Among these, 96.4% reported using fungicides, 68.2% insecticides, and 28.7% herbicides.

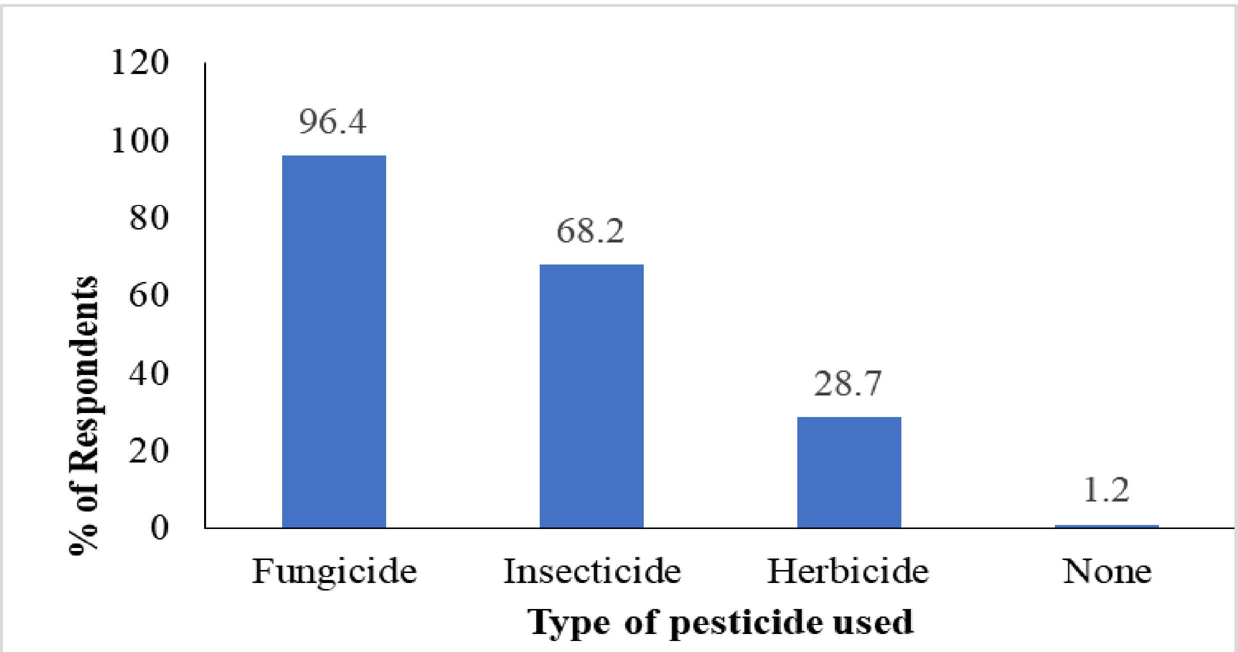


**Figure 4.1:** Type of pesticides used in potato farming

Table 4.3 shows the active ingredients in the pesticides commonly used by potato farmers in Nyandarua County. The major active ingredients in the fungicides being used are mancozeb, metalaxyl, and cymoxanil while α-cypermethrin, imidacloprid, and ɣ-cyhalothrin are the major active ingredients contained in the most commonly used insecticides. Glyphosate, 2,4-D, and atrazine are the major active ingredients in the most commonly used herbicides for the management of weeds.

**Table 4.3:** Pesticides commonly used by small-scale potato farmers in the management of pests, diseases and weeds diseases in Nyandarua County

| Pesticide | Active ingredients | Respondents (n) | Percentage (%) |
|---|---|---|---|
| Fungicides | Manconzeb+Cymoxanil | 247 | 98.8 |
| | Fluopicolide +Propamocarb | 146 | 58.4 |
| | Manconzeb + Metalaxyl | 247 | 98.8 |
| | Famoxadime + Cymoxanil | 19 | 7.6 |
| | Propineb + Cymoxanil | 22 | 8.8 |
| | Mandipropamid | 17 | 6.8 |
| | Chlorothalonil | 2 | 0.8 |
| | Dimethomorph+Fluazinam | 5 | 2 |
| | Dimethomorph | 2 | 0.8 |
| | Copper hydroxide | 2 | 0.8 |
| Herbicides | Glyphosate | 71 | 2.84 |
| | Metribuzin | 11 | 4.4 |
| | Dichlophenyl Acetic Acid) [2,4-D] | 34 | 13.6 |
| | Nicosulfuron + Mesotrione + Atrazine | 16 | 6.4 |
| Insecticides | Malathion | 3 | 1.2 |
| | Alpha-cypermethrin | 137 | 54.8 |
| | Spirotetramat + Flubendiamide | 6 | 2.4 |
| | Lambda-cyhalothrin | 135 | 54 |
| | Imidacloprid + Beta-cyfluthrin | 145 | 58 |
| | Fluopyram | 10 | 4 |
| | Thiamethoxam+Lambda-cyhalothrin | 4 | 1.6 |

### 4.4 Potato on-farm pesticide application practices

Table 4.4 shows the current practices in pesticide use among the potato farmers interviewed. The majority of the respondents mix fungicides and liquid fertilizers (54%) while the minority (14.8%) do not mix pesticides. The majority of farmers (74.8%) get instructions on application rates from agrochemical retailers, while 13.2% ask other farmers. Only 12% of the farmers follow the dosage guidelines provided by the manufacturers **(Appendix 4).** The majority of farmers (60.8%) apply fungicides on their crops after every 7 days. Some, (10%) apply pesticides only when they detect pests or diseases affecting their farms. Other farmers, (16.4%) make pesticide applications every two weeks while 12.8% of farmers use pesticides on their crops three times per month on a routine basis, regardless of observable pest or disease pressure. The majority of the farmers (98.8%) apply pesticides during the tuber development stage of the potato crop. Only 31.2% of the respondents treat the soil before planting while 22.8 % apply pesticides during the crop's emergence stage after planting. The majority of the farmers (53.2%) harvest potato tubers three weeks after applying pesticides. Meanwhile, 36.8% of the farmers harvest four weeks after applying the pesticides while others (10%) harvest after five to six weeks.

**Table 4.4:** Characteristics of potato on-farm pesticide practices

| Category of Practice | Practice | Response (n=250) | Percentage (%) |
|---|---|---|---|
| Mixing pesticides | Mixing of fungicide & foliar fertilizers | 135 | 54 |
| | Mixing of fungicide & insecticide | 78 | 31.2 |
| | Don't mix pesticides | 37 | 14.8 |
| Application rates/dosage of pesticides source of instruction | Follow the manufacturer's instructions | 30 | 12 |
| | Asks from the *agro vet | 187 | 74.8 |
| | Asks from other farmers | 33 | 13.2 |
| Frequency of application | Every 7 days | 152 | 60.8 |
| | Every two weeks | 41 | 16.4 |
| | Three times a month | 32 | 12.8 |
| | Spray when the farm is attacked by pests and diseases | 25 | 10 |
| Timing | Before planting | 78 | 31.2 |
| | During emergence | 57 | 22.8 |
| | During tuber development | 247 | 98.8 |
| Pre-harvest interval | 3 weeks | 92 | 36.8 |

*Agro-vet: A store or business that supplies agricultural products and service

## 4.5 Potato postharvest handling practices

The potato postharvest handling practices are presented in table 4.5. Only 26% of the respondents' sort potatoes before selling. The majority of the respondents (67%) use closed-back lorries or pick-up trucks to transport potatoes from the farm to the market, 24% use motorbikes while 9% of the respondents use open-back hand-pulled carts. Most of the respondents (77%) carry out loading and unloading processes carefully avoiding impact forces while 23% roughly handle potatoes during loading and unloading processes, which could potentially lead to bruising and damage. From observations, 88% of the respondents expose potatoes to sunlight or artificial light during handling or storage.

The duration of storage of the period between harvest and the next supply or consumption varies among the respondents. The majority (11%) store potatoes for 1-3 weeks, 8% for 1 month, 1% for 3 to 6 weeks, 3% for 3 months and 1% of the respondents' storage duration for the potatoes depends on demand. Regarding the place of storage, 5% of the respondents' store potatoes in a cool, dry place, 5% in piles, 6% in a dark room, 4% in a room with enough light and 5% cover potatoes with grass during storage.

**Table 4.5:** Potato postharvest handling practices among traders

| Category of practice | Sub-practice | Frequency(n=100) | Percentage |
|---|---|---|---|
| Mode of transport | Open back hand-pulled cart | 9 | 9 |
| | Closed-back lorry/pick up | 67 | 67 |
| | Motorbike | 24 | 24 |
| Loading and unloading processes | Carefully avoiding impact | 7 | 7 |
| | Rough handling with the potential of bruising and damage | 5 | 5 |
| Exposure to sunlight | Yes | 10 | 10 |
| Storage | Cool dry place | 5 | 5 |
| | In piles | 5 | 5 |
| | In a dark room | 6 | 6 |

| | | | |
|---|---|---|---|
| | In a room with enough light | 4 | 4 |
| | Cover with grass | 5 | 5 |
| Duration of storage | 1-3 weeks | 11 | 11 |
| | 1 month | 8 | 8 |
| | 3-6 weeks | 1 | 1 |
| | 3 months | 3 | 3 |
| | Depends on demand | 1 | 1 |

**4.6 The effect of the handling practices on pesticide residues and glycoalkaloid levels in potato tubers**

**4.6.1 Method validation for determination of pesticide residues**

Interfering peaks were not observed in the expected retention windows for the reagent and matrix blanks. Calibration curves were linear with correlation coefficients, $r \geq 0.995$ for all the analytes. The recovery range was of 75.2 to 114.6% and the relative standard deviation ≤15%. The LOD values were between 0.01 and 0.03 µg/kg, and LOQ values between 0.03 and 1.5 µg/kg.

**4.6.2 The effect of on-farm pesticide application practices on the levels of pesticide residues in potato tubers**

The findings presented in Table 4.6 show that the mean herbicide residue levels were influenced by various on-farm practices. There were significant variations ($p \leq 0.05$) in the mean residue levels of 2,4-D, atrazine, and glyphosate among the different practices. Potato tubers obtained from farmers who adhered to the manufacturer's instructions for pesticide application rates had no residues for three herbicides (2,4-D, atrazine, and metolachlor**)** and had significantly lower levels ($p \leq 0.05$) of glyphosate residues (0.44 ±0.3 µg/kg) compared to those who received advice from agro vets (4.63 µg/kg) or other farmers (0.60±0.3 µg/kg).

Potato tubers obtained from farmers who observed a pre-harvest interval of three weeks had significantly ($p \leq 0.05$) higher mean residues for 2,4-D (3.33 µg/kg) while tubers from farmers who applied pesticides when they detected pests and diseases had the lowest residue levels of 2,4-D (1.63 µg/kg). The mean residue levels of metolachlor did not differ significantly among the practices. As the preharvest interval increased from 3 weeks to 4 weeks and 5 to 6 weeks, there was a noticeable decrease in the levels of herbicide residues.

**Table 4.6:** Effect of on-farm pesticide practices on the levels of herbicide residues in potatoes

| On-farm pesticide practice | 2-4, D (µg/kg) | Atrazine (µg/kg) | Metolachlor (µg/kg) | Glyphosate (µg/kg) |
|---|---|---|---|---|
| **Application rates** | | | | |
| Follow the manufacturer's instructions | - | - | - | 0.60±0.27[b] |
| Asks from the agro vet | - | 1.34±0.52[abc] | 3.29±0.58[a] | 4.63±1.78[a] |
| Asks from other farmers | 1.92±0.01[bcd] | 1.86±0.19[a] | 3.8±3.8[a] | 0.44±0.3[b] |
| **Frequency of application** | | | | |
| Every 7 days | - | 0.73±0.73[abc] | - | - |
| Every two weeks | - | - | - | - |
| Three times a month | - | 0.7±0.31[abc] | - | - |
| Spray when the farm is attacked by pests and diseases | 1.63±0.39[cd] | 0.95±0.23[abc] | - | - |
| **Timing** | | | | |
| Before planting | - | - | - | - |
| During tuber development | - | 0.43±0.29[f] | - | 0.51±0.35[b] |
| **Preharvest interval** | | | | |
| 3 weeks | 3.33±0.26[a] | 1.6±0.24[a] | - | - |
| 4 weeks | 2.81±0.33[abc] | 0.98±0.28[abc] | 0.65±0.44[a] | - |
| 5 to 6 weeks | 1.67±0.4[cd] | 0.49±0.22[abc] | - | - |

Values of a parameter in a column, followed by different superscript letters are significantly different at $p \leq 0.05$. Values are means (µg/kg) ± standard error. (-) means that the residue levels were not detectable/could not be quantified.

Table 4.7 shows the levels of fungicide residues in potato tubers as influences by on-farm practices. When pesticides are mixed, residue levels in potatoes showed significant variations across the three fungicides. Azoxystrobin, mancozeb, and metalaxyl levels were 15.3±4.98 µg/kg, 12.05±3.05 µg/kg, and 15.46±3.69 µg/kg, respectively.

Following the manufacturer's instructions application rates resulted in significantly lower residue levels for mancozeb (0.45±0.31 µg/kg) and metalaxyl (0.401±0.27 µg/kg). Conversely, when farmers sought advice from agro-vets, residue levels were higher, particularly for azoxystrobin (31.008±5.44 µg/kg). When farmers relied on information from other farmers, the residue levels were highest for azoxystrobin (49.55±0.12 µg/kg) and lower for mancozeb (2.2±1.76 µg/kg) and metalaxyl (7.10±4.76 µg/kg).

The weekly application resulted in the highest mancozeb residues (24.77±5.28 µg/kg) and lower levels of azoxystrobin (5.81±1.33 µg/kg) and metalaxyl (12.13±3.15 µg/kg). Application every two weeks reduced residues for azoxystrobin (8.18±0.08 µg/kg) and metalaxyl (12.23±2.49 µg/kg), but residues for mancozeb remained high (14.73±2.78 µg/kg). Applications three times a month showed moderate residues across all fungicides. Notably, spraying only in response to pest attacks led to very high residues of azoxystrobin (32.8±0.09 µg/kg) and considerable levels of mancozeb (22.81±2.63 µg/kg) and metalaxyl (12.09±2.85 µg/kg). Applying fungicides before planting resulted in moderate azoxystrobin residues (9.39±4.12 µg/kg) and minimal residues for the other two fungicides. Applying fungicides during flowering resulted in minimal residues for mancozeb (0.43±0.29 µg/kg) and metalaxyl (0.51±0.35 µg/kg).

**Table 4.7:** Effect of on-farm pesticide practices on the levels of fungicide residues in potatoes

| Category of practice | On-farm pesticide practice and risk factors | Azoxystrobin (µg/kg) | Mancozeb (µg/kg) | Metalaxyl (µg/kg) |
|---|---|---|---|---|
| Mixing of pesticides | Pesticide mixing | $15.3±4.98^{c}$ | $12.05±3.05^{cde}$ | $15.46±3.69^{a}$ |
| Application rates | Follow the manufacturer's instructions | - | $0.45±0.31^{f}$ | $0.401±0.27^{c}$ |
| | Asks from the agro vet | $31.008±5.44^{b}$ | $4.77±2.13^{cdf}$ | $3.97±1.05^{bc}$ |
| | Asks from other farmers | $49.55±0.12^{a}$ | $2.2±1.76^{cf}$ | $7.10±4.76^{abc}$ |
| Frequency of application | Every 7 days | $5.81±1.33^{cd}$ | $24.77±5.28^{a}$ | $12.13±3.15^{ab}$ |
| | Every two weeks | $8.18±0.08^{cd}$ | $14.73±2.78^{abe}$ | $12.23±2.49^{ab}$ |
| | Three times a month | $6.19±4.2^{cd}$ | $14.21±3.12^{bde}$ | $8.61±2.43^{abc}$ |
| | No timing | - | - | $3.52±2.35^{bc}$ |
| | Spray when the farm is attacked by pests and diseases | $32.8±0.09^{b}$ | $22.81±2.63^{ab}$ | $12.09±2.85^{ab}$ |
| Timing | Before planting | $9.39±4.12^{cd}$ | - | - |
| | During emergence/tuber initiation | - | - | - |
| | During weeding | - | - | - |
| | During flowering | - | $0.43±0.29^{f}$ | $0.51±0.35^{c}$ |
| Preharvest interval | 3 weeks | - | $2.93±0.27^{cf}$ | $3.15±0.3^{bc}$ |
| | 4 weeks | $4.59±3.12^{cd}$ | $2.83±0.23^{cf}$ | $2.75±0.21^{bc}$ |
| | 5 to 6 weeks | $1.32±0.9^{d}$ | $2.56±0.29^{cf}$ | $2.01±0.36^{bc}$ |

Values of a parameter in a column, followed by different superscript letters are significantly different at $p \leq 0.05$. Values are means (µg/kg) ± standard error. (-) means that the residue levels were not detectable/could not be quantified.

Table 4.8 presents findings on how different on-farm pesticide practices influence the residual levels of six insecticides in potatoes: imidacloprid, fenitrothion, chlorpyrifos, α-cypermethrin, λ-cyhalothrin, and deltamethrin. Mixing pesticides led to varied residue levels, with fenitrothion (25.32±4.67 µg/kg) and chlorpyrifos (24.65±2.79 µg/kg) showing significantly high residues. In contrast, imidacloprid (0.44±0.3 µg/kg) and α-cypermethrin (0.4±0.27 µg/kg) had lower residue levels, and λ-cyhalothrin (7.40±0.84 µg/kg) had moderate levels, while deltamethrin was not detected.

Following the manufacturer's instructions application rates generally resulted in lower residue levels for most insecticides. For instance, imidacloprid (0.37±0.25 µg/kg) and fenitrothion (0.13±0.09 µg/kg) were present at minimal levels, while chlorpyrifos was not detected. However, λ-cyhalothrin showed a higher residue level (12.17±3.24 µg/kg). Application rates by farmers who consulted the agrovets resulted in higher residues of imidacloprid (3.09±0.05 µg/kg), while those who sought advice from other farmers further increased the residue levels (3.33±0.03 µg/kg).

The frequency of application also significantly affected the residue levels. Weekly applications led to moderate residues of imidacloprid (1.7±0.53 µg/kg) and α-cypermethrin (1.84±1.84 µg/kg). Bi-weekly applications resulted in increased imidacloprid residues (2.38±0.59 µg/kg), while applying three times a month resulted in significant residues of chlorpyrifos (13.18±3.17 µg/kg) and λ-cyhalothrin (9.3±2.23 µg/kg). Spraying only when pests or diseases attack the farm resulted in the highest residues across multiple insecticides, including α-cypermethrin (22.36±5.37 µg/kg), fenitrothion (19.25±4.76 µg/kg), and chlorpyrifos (11.01±2.22 µg/kg).

Applying insecticides during flowering resulted in higher residues for imidacloprid (3.01±0.05 µg/kg), chlorpyrifos (4.7±2.28 µg/kg), and α-cypermethrin (11.48±4.85 µg/kg). The residues of imidacloprid (1.31±0.44 µg/kg), fenitrothion (0.37±0.25 µg/kg), chlorpyrifos (0.21±0.14 µg/kg), and α-cypermethrin (1.35±0.92 µg/kg) were significantly lower at 5 to 6 weeks compared to shorter pre-harvest interval.

**Table 4.8:** Effect of on-farm pesticide practices on the levels of insecticide residues in potatoes

| Category of practice | Practice | Imidacloprid (µg/kg) | Fenitrothion (µg/kg) | Chlorpyrifos (µg/kg) | α-Cypermethrin (µg/kg) | λ-cyhalothrin (µg/kg) | Deltamethrin (µg/kg) |
|---|---|---|---|---|---|---|---|
| Mixing of pesticides | Mixing of pesticides | 0.44±0.3$^{d}$ | 25.32±4.67$^{a}$ | 24.65±2.79$^{a}$ | 0.4±0.27$^{c}$ | 7.40±0.84$^{ab}$ | - |
| Application rates | Follow the manufacturer's instructions | 0.37±0.25$^{d}$ | 0.13±0.09$^{b}$ | - | - | 12.17±3.24$^{a}$ | 2.02±0.07 |
| | Asks from the agro vet | 3.09±0.05$^{ab}$ | - | - | - | - | - |
| | Asks from other farmers | 3.33±0.03$^{a}$ | - | - | - | - | - |
| Frequency of application | Every 7 days | 1.7±0.53$^{abcd}$ | - | - | 1.84±1.84$^{bc}$ | - | - |
| | Every two weeks | 2.38±0.59$^{abc}$ | - | - | - | - | - |
| | Three times a month | 1.51±0.37$^{abcd}$ | - | 13.18±3.17$^{b}$ | - | 9.3±2.23$^{ab}$ | - |
| | No timing | 1.58±0.51$^{abcd}$ | - | - | - | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Spray when the farm is attacked by pests and diseases | 2.1±0.51$^{abcd}$ | 19.25±4.76$^{a}$ | 11.01±2.22$^{bc}$ | 22.36±5.37$^{a}$ | 11.5±2.87$^{a}$ | - |
| Timing | Before planting | - | - | - | - | - | - |
| | Emergence/tuber initiation | - | - | - | - | - | |
| | Weeding | | - | - | - | - | - |
| | During flowering | 3.01±0.05$^{ab}$ | - | 4.7±2.28$^{cd}$ | 11.48±4.85$^{ab}$ | 3.6±1.67$^{bc}$ | |
| Preharvest interval | 3 weeks | 1.87±0.28$^{abcd}$ | - | 0.18±0.13$^{d}$ | 6.02±3.76$^{bc}$ | - | - |
| | 4 weeks | 1.55±0.39$^{abcd}$ | - | 0.17±0.12$^{d}$ | 4.61±3.13$^{bc}$ | - | - |
| | 5 to 6 weeks | 1.31±0.44$^{bcd}$ | 0.37±0.25$^{b}$ | 0.21±0.14$^{d}$ | 1.35±0.92$^{bc}$ | 0.36±9.24$^{c}$ | - |

Values of a parameter in a column, followed by different superscript letters are significantly different at $p \leq 0.05$. Values are means (µg/kg) ± standard error. (-) means that the residue levels were not detectable/could not be quantified.

### 4.6.3 Effect of post-harvest handling practices on the levels of glycoalkaloids in potato tubers

Figure 4.2 shows the effect of post-harvest handling practices on the levels of glycoalkaloids in *Shangi* variety potato tubers. The levels of α-solanine, α-chaconine and total glycoalkaloid differed significantly among the various handling practices. Potatoes exposed to light conditions had the highest levels of α-solanine (320.33 mg/kg dry weight basis), α-chaconine (513.71 mg/kg dry weight basis), and total glycoalkaloids content (834.03 mg/kg dry weight basis). Potatoes with mechanical injuries had lower levels of α-solanine (165.37 mg/kg dry weight basis), α-chaconine (198.37 mg/kg dry weight basis), and total glycoalkaloids content (357.04 mg/kg dry weight basis dry weight basis) compared to the other treatments.

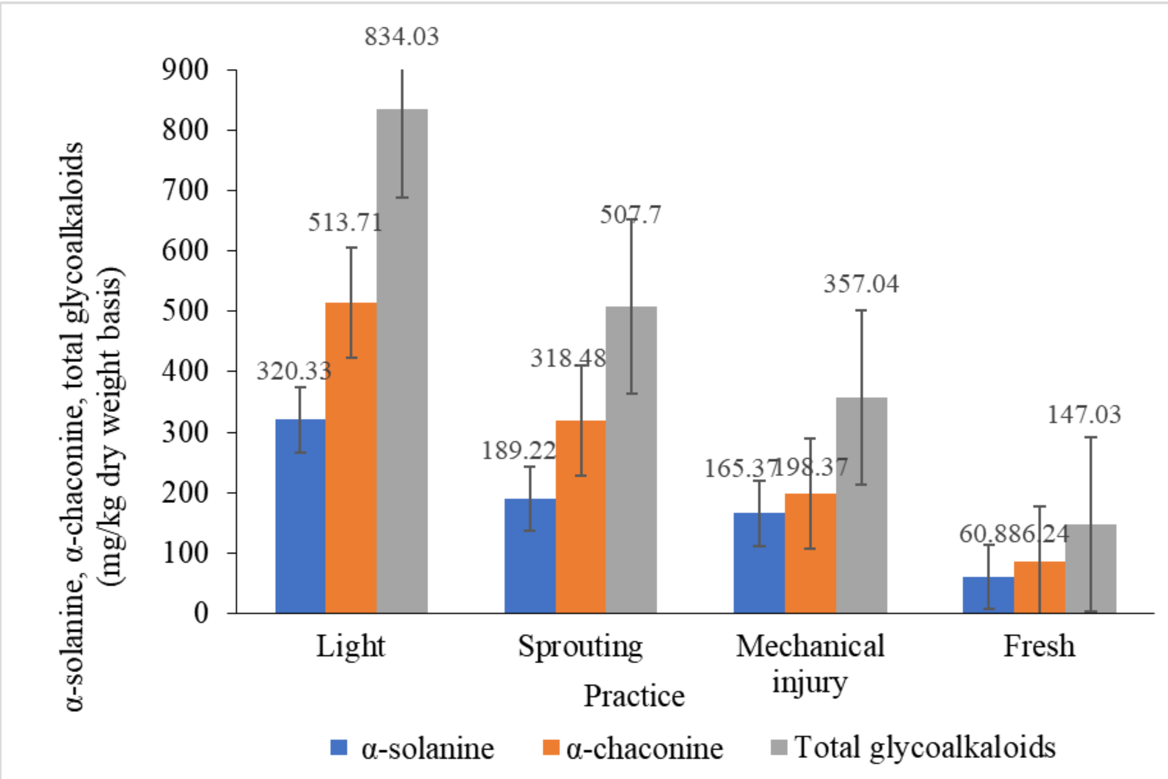


**Figure 4.2:** Effect of post-harvest handling practices on the levels of glycoalkaloids in potato tubers

### 4.7 The effect of common processing methods on the pesticide residue levels in potatoes

Table 4.10 provides data on the pesticide's residue levels before and after different potato cooking treatments. The different processing methods had statistically significant difference ($p \leq 0.05$) in residue levels for each pesticide.

Frying resulted in the highest significant reduction of 2,4-D residues, from 9.39 µg/kg to 2 µg/kg (78.7%). Baking proved to be the most efficient method in reducing the atrazine residues (1.86 µg/kg to 0.97 µg/kg (47.8%). Boiling was the most effective in reducing metolachlor residues from 3.8 µg/kg to 1.2 µg/kg (68.4%). Roasting and steaming were less effective compared to other methods but still resulted in reductions of the initial residue levels.

Overall, frying method was the most effective method in the reduction of fungicides. It significantly reduced the levels of azoxystrobin from 49.55 µg/kg to 3.78 µg/kg (92.4%) and metalaxyl from 15.46 µg/kg to 2.06 µg/kg (86.7%). Steaming showed significant reductions, especially for metalaxyl, from 15.46 µg/kg to 4.11 µg/kg (73.4%), and azoxystrobin from 49.55 µg/kg to 16.06 µg/kg (67.6%). Roasting also reduced fungicide levels, but less effectively than other methods. Boiling was highly effective for metalaxyl residues, reducing them from 15.46 µg/kg to 1.35 µg/kg (91.3%), but less so for azoxystrobin, (49.55 µg/kg to 44.32 µg/kg (10.6%).

Frying resulted in the highest significant reduction of α-cypermethrin from 22.36 µg/kg to 2.16 µg/kg (90.3%). In contrast, frying showed least effectiveness (21.3%) in the reduction of fenitrothion residues. Also, worthy noting is that frying did not reduce the residue levels of fenitrothion (from 25.32 µg/kg to 19.93 µg/kg) and chlorpyrifos (from 24.65 µg/kg to 12.01 µg/kg) below the maximum residue limits (MRLs). Frying (42.8%) and boiling (42.5%) were equally effective in the reduction of imidacloprid while roasting had the least efficacy (17.28%). Boiling exhibited the highest reduction of fenitrothion residues from 25.32 µg/kg to 6.76 µg/kg (73.3%) and α-cypermethrin residues in potatoes with a 92.3% decrease (22.36 µg/kg to 1.72 µg/kg). Baking showed the best efficacy in the reduction of α-cypermethrin from 22.36 µg/kg to 1.72 µg/kg (92.3%) and least efficacy in the reduction of imidacloprid from 3.33 µg/kg to 1.92 µg/kg (42.3 %). Steaming showed the highest reduction of imidacloprid from 22.36 µg/kg to 2.23 µg/kg (90%) and least reduction of α-cypermethrin from 22.36 µg/kg to 8.4 µg/kg (62.4%). Roasting was less effective in reducing the levels of pesticide residues compared to other methods.

**Table 4.10:** Effect of common processing methods on herbicide residue levels in potato products

| PM | 2-4, D | ATZ | MTC | GPS | AZX | MCB | MTL | IDC | FTT | CPF | CPM | CHT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial residue level (µg/kg) | 9.39 | 1.86 | 3.8 | 4.63 | 49.55 | 22.81 | 15.46 | 3.33 | 25.32 | 24.65 | 22.36 | 12.17 |
| Frying | 2.0±0.12$^{a}$ | 1.16±0.34$^{b}$ | 3.07±0.02$^{d}$ | 1.92±0.02$^{a}$ | 3.78±0.2$^{a}$ | 19.07±0.02$^{d}$ | 2.06±0.01$^{b}$ | 1.91±0.02$^{a}$ | 19.93±0.03$^{d}$ | 12.01±0.03$^{d}$ | 2.16±0.02$^{b}$ | 2.96±0.02$^{b}$ |
| Baking | 3.78±0.03$^{b}$ | 0.97±0.02$^{a}$ | 2.2±0.031c | 3.44±0.01$^{d}$ | 9.85±0.02$^{b}$ | 20.96±0.02$^{e}$ | 7.02±0.03$^{d}$ | 1.92±0.3$^{a}$ | 6.76±0.01$^{a}$ | 9.06±0.02$^{b}$ | 1.72±0.16$^{a}$ | 3.98±0.02$^{c}$ |
| Roasting | 4.76±0.56$^{c}$ | 1.63±0.03$^{e}$ | 3.11±0.02$^{e}$ | 3.62±0.01$^{e}$ | 27.4±0.01$^{d}$ | 16.76±0.01$^{c}$ | 8.29±0.02$^{e}$ | 2.75±0.01$^{d}$ | 11.73±0.02$^{c}$ | 10.6±0.02$^{c}$ | 13.57±0.02$^{e}$ | 6.03±0.01$^{e}$ |
| Boiling | 5.2±0.09$^{d}$ | 1.51±0.02$^{d}$ | 1.2±0.45a | 3.03±0.02$^{c}$ | 44.32±0.03$^{e}$ | 14.04±0.02$^{a}$ | 1.35±0.01$^{a}$ | 1.92±0.3$^{a}$ | 6.76±0.01$^{a}$ | 9.06±0.02$^{b}$ | 1.72±0.16$^{a}$ | 3.98±0.02$^{c}$ |
| Steaming | 5.74±0.04$^{e}$ | 1.45±0.02$^{c}$ | 1.74±0.01$^{b}$ | 2.47±0.02$^{b}$ | 16.06±0.01$^{c}$ | 16.35±0.02$^{b}$ | 4.11±0.01$^{c}$ | 2.23±0.02$^{c}$ | 7.89±0.01$^{b}$ | 6.72±0.02$^{a}$ | 8.4±0.01$^{d}$ | 4.32±0.02$^{d}$ |
| **Codex MRLs (µg/kg)** | **200** | **50** | **50** | **500** | **7000** | **300** | **20** | **10** | **10** | **10** | **50** | **50** |

Values of a parameter in a column, followed by different superscript letters are significantly different at $p \leq 0.05$. Values are means ± standard error**.**

**Key; PM-processing method; 2,4-D**; **ATZ**-Atrazine; **MTC**-Metalochlor; **GPS**-Glyphosate; **AZX-**Azoxystrobin**; MCB-**Mancozeb**; MTL-**Metalaxyl; **IDC**-Imidacloprid; **FTT**-Fenitrothion; **CPF-**Chlorpyrifos; **CPM**-α-Cypermethrin; **CHT**-λ-cyhalothrin

## 4.8 The effect of common processing methods on the glycoalkaloid levels in potatoes

The various processing methods resulted to reduced glycoalkaloid contents, both α-chaconine, and α-solanine in the *Shangi* potato variety as illustrated in Figure 4.3. Frying resulted in the highest decrease of α-chaconine and α-solanine from 200.4 mg/kg to 96.75 mg/kg (51.72%) and 129.38 mg/kg to 75.31 mg/kg (41.79%) of dry matter respectively while steaming resulted to the least decrease of α-Chaconine to 182.10 (9.13%) and 121.18 α-solanine (6.34%).

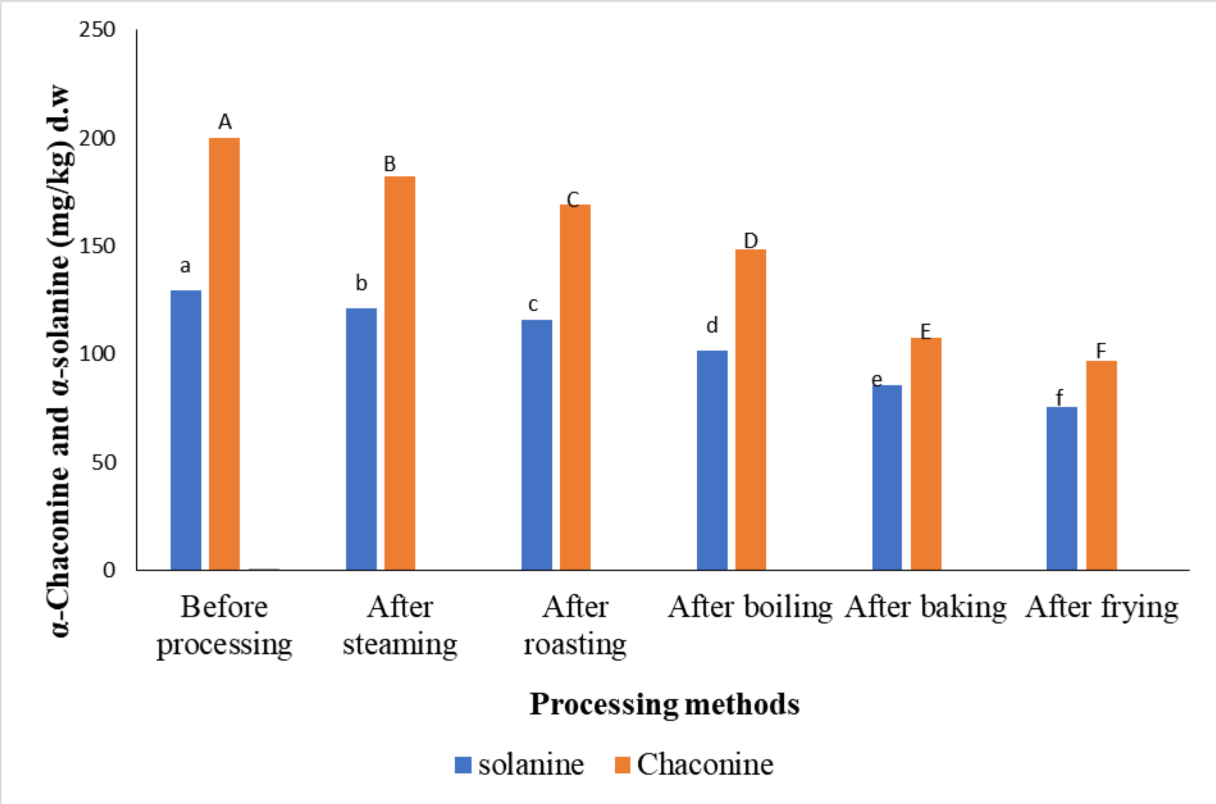


**Figure 4.3:** Effect of common processing methods on the α-chaconine and α-solanine levels

The contents (mg/kg d.m) of α-chaconine and α-solanine in the *Shangi* potato variety after different processing methods. (a-d) mean values of solanine contents with different letters differ significantly at $p \leq 0.05$ A–D– mean values of α-chaconine contents with different letters differ significantly at $p \leq 0.05$

# CHAPTER FIVE

# DISCUSSIONS

## 5.1 Socio-demographic characteristics of the farmers

In this study (Table 4.1), male farmers were the majority (54.4%). The dominance of male respondents can be explained by gender norms and cultural practices that often grant men rights to own and have authority over land use and productive resources. This limits women's ability to access land and their decision-making power on land use. Women often face constraints in accessing agricultural inputs, credit, extension services, and technology due to gender-based discrimination and societal norms (Langat, 2016; Nguetti *et al*., 2018; Taiy *et al*., 2017; Wamuyu, 2019).

The age of a farmer significantly influences their decision-making power in the production of crops (Dhraief *et al*., 2018). In this study, the farmers above 40 years old were the majority (80.4%) while those below 40 years were the minority (19.6%). This is comparable to a study by Arimi *et al*. (2014) who reported that most African farmers are adults between the ages of 40 and 50. This could be because agriculture tends to attract individuals with established experience, such as those with land ownership or a risk-averse mindset. Additionally, younger people may be not interested in farming and thus seek employment opportunities in urban areas (Kilonzi *et al*., 2024; Nyalugwe *et al*., 2022).

Majority of respondents (87.5%) had formal education, while 12.4% had not received formal education. This finding aligns with a study in Molo Sub-County, Kenya by Chepkoech (2022) which reported that 92.8% of potato farmers had attained formal education, enabling them to comprehend technical information on potato production practices. Farmers with formal education are more knowledgeable about crop production management techniques (Emana *et al*. 2017; Mwangi *et al.* 2015) and are more likely to comprehend concepts taught in training related to good potato handling practices for safe potato products. On the other hand, those without formal education may have difficulty adopting good handling practices, which can impact farmers' overall productivity.

The farmers' experience in potato farming is determined by the number of years they have been involved in cultivating the crop. Findings of this study noted that 52.4% reported having less than five years implying that they have less experience in potato production. Some of the reasons as to why this could be happening is the fact that some farmers are still young and not yet deeply involved in potato farming, while others may have recently joined the industry as a secondary source of income in addition to other activities.

## 5.2 Socio-demographic characteristics of the traders

The majority of the respondents (64%) were female, indicating a significant presence of women in the potato trading activity (Table 4.2). This finding is consistent with existing literature highlighting women's role in the agricultural value chains and informal trade sectors in many countries that are developing (Ngendo *et al*., 2018; Sassen *et al*., 2018; Wamuyu, 2019).

On age distribution, the study shows that majority of the respondents (35%) were within the 50-59 years old age group, while the youngest age group (18-29 years) were the least (3%). This age distribution shows that the trading activity is mainly undertaken by older individuals, which could be attributed to factors such as experience, established networks, and access to resources (Kisang *et al.,* 2025). However, the low representation of youth in trading activity could be a concern, as it may indicate barriers to entry or a lack of interest among younger generations.

Furthermore, respondents had relatively low education attainment with 37% not completing primary education and only 2% attaining tertiary education. This finding aligns with the literature highlighting the prevalence of low educational attainment among informal sector workers and smallholder farmers in countries that are developing (Mwaura, 2017; Okunlola *et al*., 2019). Low levels of education can have implications for access to information, adoption of new technologies, and overall economic empowerment (Ndung'u *et al*., 2023).

The socio-demographic characteristics observed in this study underscore the importance of considering gender, age, and educational factors in designing and implementing interventions to support and empower traders in the agricultural value chain. Targeted efforts may be required to address gender inequalities, facilitate youth participation, and provide educational opportunities or alternative pathways to knowledge and skill development for traders (Lowder *et al*., 2016).

## 5.3 Pesticides commonly used in potato production

Pesticides use in agricultural production is a global emerging issue threatening the health of the environment, chemical applicants and the consumers of agricultural products. This study showed that almost all the respondents (98.8%) rely only on synthetic pesticides for pests, diseases and weed control in potato farms (Figure 4.1). This heavy reliance on chemical control methods could stem from a lack of knowledge about alternative approaches like biological management and integrated management strategies (Agong *et al*., 2021) or a perception that these alternatives are less convenient. Also, it could be attributed to the availability and accessibility of the pesticides. Among the pesticides used, fungicides are the most common due to the increased cases of fungal diseases such as late and early blight. Gianessi and Williams (2011) noted that approximately 93 to 100% of potato farmers in Kenya exclusively use synthetic pesticides to eradicate late blight. This could be due to the recycling of seeds from previous harvests, continuous monocropping, and poor plant debris management in the region (Agong *et al*., 2021; Ateka *et al*., 2022). Mancozeb and metalaxyl are extensively used more than other fungicides. This is similar to a report by Agong *et al*. (2021) and Kurui *et al*. (2014) who established that pesticides containing mancozeb and metalaxyl active ingredients are the most frequently used in potato production in Elgeyo Marakwet County and Nyandarua County, Kenya. This could be attributed to the availability and accessibility of the fungicides containing these active ingredients in the local markets.

### 5.4 Potato on-farm pesticide application practices

Proper pesticide application methods are critical for both effectively managing pests and diseases as well as ensuring safe use that minimizes risks (Momanyi *et al*., 2019). This study has shown significant gaps in proper pesticide usage among farmers. There is a widespread lack of adherence to usage guidelines regarding the mixing of pesticides, application rates, spray frequency, the timing of applications, and pre-harvest intervals (Table 4.4). Studies point this misuse happens because many small-scale farmers lack technical background, scientific training on chemicals, and access to agricultural experts through crop adviser programs (Mengistie *et al.,* 2017). Addressing this knowledge deficit through targeted training programs and accessible extension services from qualified professionals is crucial to ensure the safe and responsible pesticides use in potato farming.

Safe application rates of pesticides in crop fields helps to comply with regulatory standards and in turn reducing human health risks (Li, 2023). In this study, the majority of farmers (74.8%) receive instructions on application rates from agrochemical retailers, while 13.2 % ask other farmers. Only 12% of the farmers follow the dosage guidelines provided by the manufacturers. Most of the farmers (74.63%) rely on agro vets' advice on application rates rather than the manufacturer’s instructions. This could be because these agro vets have day-to-day experience recommending effective chemicals in the area, so farmers trust them to provide useful guidance. However, as businesses, these agro vets may put sales first before properly training new or beginning farmers on the safe use of pesticide options. They assume farmers already know enough when purchasing chemicals. This becomes concerning with more and more new pesticide products being made to protect crops (Nguetti *et al.,*2018). Similar to reports from other studies by Nuwamanya *et al*. (2023), Onowona-Kwakye *et al*. (2020) and Sookhtanlou *et al*. (2022) this study found that most farmers use higher concentrations than the recommended dosage, in an attempt to increase effectiveness against pests, diseases and weeds. Other farmers used lower levels than recommended. Similar results have been reported in Ghana in pesticide application in cabbage farming where farmers apply less than the required dosage. This could be attributed to farmers' inability to read and comprehend pesticide labels (Amoabeng *et al*., 2017). Also, this finding could be associated with the cost of the product and the perception of the farmers about its effectiveness. However, this study does not present any conclusive reasons about the relationship but recommends this for further investigation.

In this study, most of the farmers apply fungicides to their crops every 7 days which increases the risk of having residues in the crops while others (42.15%) applied pesticides on their crops three times per month on a routine basis, regardless of observable pest or disease pressure. This could be because of a knowledge gap since most farmers lack sufficient knowledge about proper fungicide application practices. They may not be aware of the importance of scouting for actual pest or disease presence before applying pesticides. Also, it could be a preventive measure to avoid potential crop losses due to the frequent and predictable incidences of potato crop damage in the past due to fungal diseases in the region.

The survey results show differing timelines among farmers regarding how long they wait between the final pesticide application and harvesting their potato crop. The majority of the farmers (53.2%) harvest potato tubers three (3) weeks after applying pesticides. Meanwhile, 36.8% of the farmers harvest four (4) weeks after spraying while others (10%) harvest after five to six weeks. This could be possibly driven by the peaking market demand, financial pressures, or lack of knowledge on the importance of adhering to pre-harvest interval guidelines. A similar finding has been reported in Ghana among cabbage farmers where farmers do not observe the appropriate time interval between the date of the last spray and harvest due to market demand (Amoabeng *et al*., 2017).

This study also showed that 85% of the respondents mixed several pesticides. Farmers mix pesticides in the hope that they will get a new formulation with high toxicity, and preventive measures if there are pests or other diseases that will attack their crops (Bhandari *et al*., 2020; Demmi and Sicchia, 2021). According to Fosu-Mensah *et al*. (2022), it could also be an attempt by most farmers to on save time and labour that would be spent spraying one chemical at a time. Using pesticides this way is not on target and increases the cost of crop production as well as the risk of high pesticide residue accumulation in crops and the environment (Widada *et al.,* 2022).

### 5.5 Postharvest handling practices

In Kenya, postharvest handling practices pose a major challenge to the potato value chain (Scollard *et al*., 2022). The transportation methods, storage and handling of potato tubers can significantly influence the risk of increased glycoalkaloid levels due to exposure to unfavourable conditions. In this study (Table 4.5), the predominant modes of transport include motorbikes, closed-back lorries, and open-back pickup trucks. Motorbikes are commonly utilized for transporting potatoes to nearby markets over short distances. The practice of heaping potatoes in open pickup trucks is also prevalent among some wholesalers, leading to a potential buildup of heat, particularly during hot weather conditions. Enclosed lorries, although providing shelter from external elements, often lack proper ventilation systems, hindering temperature regulation and potentially promoting the formation of glycoalkaloids. According to Musita *et al*. (2019), direct sunlight exposure and high temperatures caused by piling or heaping of the tubers can accelerate the formation of undesirable glycoalkaloid compounds, rendering them unsafe for human consumption. During transportation, the loading and unloading processes can potentially cause bruising or mechanical injuries to the potato tubers. Only 77% of the respondents reported taking precautions to carefully avoid impact during these processes, as a means to prevent mechanical injuries or bruised tubers. Such bruises or injuries can result in increased glycoalkaloids levels in potatoes, as highlighted by Kruma and Zarins (2017). The findings in this study showed that exposing potatoes to sunlight is very common among traders irrespective of their age, level of education or gender. From observations, 88 % of the respondents exposed potatoes to sunlight or artificial light during handling or storage. A study by Musita *et al*. (2019) reported similar findings in Nairobi County among potato traders.

In Kenya, most potato farmers sell their yields immediately after harvesting, as they lack the necessary resources and machinery for storage. This results in farmers only harvesting once they have identified buyers. Only a small percentage of farmers practice on-farm storage for later sales, while those who store for household consumption usually keep potatoes in piles with no proper facilities (FAO, 2013). Traders tend to store potatoes in dark rooms in gunny bags, and those for household consumption are usually covered with grass or stored in piles. However, a significant number of traders (71%) cover their potatoes overnight with a polythene bag, which can lead to poor aeration and high temperatures that promote the development of glycoalkaloids (Musita *et al*., 2019). During the day, the potatoes are sold in the open and exposed to sunlight, increasing the risk of glycoalkaloid accumulation. The average duration of storage or time between harvest and the next supply/consumption varied among respondents. According to the respondents, potatoes tend to sell quickly due to high consumer demand, typically within 1-2 weeks. However, some traders dealing with large quantities of potatoes store them even for a month. This enables them to ensure a consistent supply for consumers and the processing industries (Azad *et al*., 2017). Tubers intended for household use may be stored for more than a month, but this can increase the risk of glycoalkaloid development if they are not stored properly and exposed to sunlight for extended periods.

### 5.6 Effect of on-farm pesticide application practices on the levels of pesticide residues in potatoes

Pesticides can penetrate into the deep layers of plant tissues from the surface (Soliman *et al*., 2001). Multiple residues of pesticides were detected in raw potato samples, including levels above the European Union (EU) and Codex maximum residue limits (Table 4.6). Levels of banned pesticides, chlorpyrifos and fenitrothion, were above the Maximum Residue Limits (MRLs) set by both the European Union (EU) and Codex Alimentarius (Codex). These pesticides were present at concentrations of 0.0245 mg/kg for chlorpyrifos and 0.025 mg/kg for fenitrothion, significantly surpassing the Maximum Residue Limit of 0.01 mg/kg. While most potato samples had pesticide levels within regulations for all chemicals analysed, concentrations surpassing EU food safety thresholds in some tubers indicated widespread issues with on-farm use patterns contributing to excessive pre-harvest residues. In this study, the levels of metalaxyl, chlorpyrifos, γ-cyhalothrin, and α-cypermethrin were within the codex MRLs but exceeded the levels reported by Oyoo *et al*. (2023) when the *Shangi* potato variety was grown under a controlled environment following good agricultural practices. This discrepancy suggests that the potato samples in this study were subject to higher pesticide application rates and less optimized timing of applications compared to good agricultural practices. Also, the manufacturer's application intervals and pre-harvest intervals were not followed as the controlled production system studied by Oyoo *et al.* (2023).

Potato tubers obtained from farmers who adhered to manufacturer's instructions for pesticide application, including herbicides, fungicides, and insecticides, had significantly lower residue levels in potatoes. For herbicides, no residues of 2,4-D, atrazine, and metolachlor were detected, and glyphosate residues were significantly lower compared to those relying on advice from agro-vets or other farmers. Similarly, adherence to manufacturer instructions resulted in the lowest fungicide residue levels, particularly for azoxystrobin, while informal advice led to significantly higher residues. This pattern was consistent for insecticides, where following standardized guidelines minimized residue levels, whereas informal advice resulted in significantly higher residues. These findings highlight the need for accurate information and adherence to recommended guidelines in managing pesticide application effectively and minimizing residue levels (Udimal *et al*., 2022).

Additionally, mixing pesticides led to high residue levels. As a root crop, potatoes rely heavily on enzymatic pathways to detoxify applied chemicals. However, exposure to pesticide mixtures can overwhelm these pathways. Many pesticides inhibit key detoxification enzymes such as cytochrome P450 monooxygenases and glutathione S-transferases. For example, organophosphate pesticides, often used for controlling pests like aphids, can inhibit esterases responsible for breaking down co-applied pyrethroids. Similarly, fungicides used to prevent blight, such as triazoles, suppress oxidative enzymes needed for the metabolism of systemic insecticides like neonicotinoids. This metabolic inhibition leads to slower degradation of pesticides and the accumulation of residues within the tubers (Ruomeng *et al*., 2023). Interactions between pesticide components further intensify this issue. For example, Fogg *et al*. (2003) noted that the half-life of isoproturon extended from 18.5 to 71.5 days in the presence of chlorothalonil, illustrating how mixtures can significantly prolong the persistence of pesticides. Such interactions, whether through chemical stabilization or microbial suppression, enhance residue persistence in soil and uptake into crops. Thus, the inhibition of detoxification enzymes and the synergistic effects of pesticide mixtures create a compounding effect, resulting in elevated residue levels in potato tubers. This shows the essence of proper management of pesticide use to ensure food safety and compliance with residue regulations.

The frequent application of pesticides in agricultural crop production results in the accumulation of pesticide residues on the land, exerting substantial pressure on agricultural ecosystems (Widada *et al*., 2022). The frequency of pesticide application significantly influenced residue levels, with weekly applications resulting in higher residues, while bi-weekly applications and strategic spraying based on pest presence led to variable levels. This can be attributed increased concentrations of the residues in the ecosystem and limited breakdown time due to frequent applications, leading to the accumulation of residues in the tubers.

Higher application rate provides more pesticide for the plant to absorb through their roots and foliage. For instance, application rates of azoxystrobin and imidacloprid had significantly ($p \leq 0.05$) higher mean residues (49.55μg/kg) and (2.27μg/kg) respectively where the respondents did not follow the manufacturer’s instructions on application rates. This could be due to the fact that most farmers don’t follow manufacturers' instructions but instead use higher concentrations than the recommended dosage, believing this will eliminate the weeds faster. As the plant pulls water and nutrients into its tissues during active growth, the concentration of any pesticide absorbed is diluted. Later in the season, when plant growth slows down, there's less water and nutrient uptake. Consequently, there is a higher concentration of pesticide residues within the plant tissues because less dilution occurs (Li & Fantke, 2023). Low and high application rates have been linked to development of resistance to some insecticides (Amoabeng *et al*., 2017; Nuwamaya *et al*., 2023).

Pesticides naturally degrade over time through various environmental processes like sunlight, microbial activity, and chemical breakdown (NPIC, 2018). The timing of application also played a crucial role; pesticide application prior to planting resulted in higher residues, whereas shorter preharvest intervals (3 weeks) significantly resulted to higher residue levels. This is because shorter pre-harvest intervals do not allow degradation of the pesticides to levels within permitted limits. This underscores the importance of appropriate timing and intervals for minimizing pesticide residues to ensure food safety (Zhang *et al*., 2022).

## 5.7 Effect of post-harvest handling practices on the levels of glycoalkaloids in potato tubers

The level of total glycoalkaloids present in commercially available potato varieties typically falls within the recommended safety threshold of 200 mg per kilogram of fresh weight for human consumption, as established by the FAO/WHO (1999). The total glycoalkaloid levels across various potato cultivars is approximately 53.00 to 153.00 mg/kg of fresh weight, well within the acceptable limits (Kirui *et al.,* 2009). However, the biosynthesis of glycoalkaloids can be rapidly induced by factors such as exposure to light, mechanical damage, and storage temperatures, which can occur at various nodes of the value chain, including while in the field, during harvest, or postharvest (Haase, 2010; Haseena *et al*., 2019; Rymuza *et al*., 2020). Post-harvest, potatoes are susceptible to mechanical damage including skin lesions and internal bruising, in addition to exposure to light and elevated temperatures during transportation, storage, and marketing processes. This results in significant food and financial losses, as well as food safety concerns due to increased glycoalkaloid accumulation (Sucha & Tomsik, 2016).

In this study, tubers exposed to sunlight (834.03 mg/kg dry weight basis) and mechanical injuries (357.04 mg/kg dry weight basis) and those stored under high temperatures (507.7 mg/kg dry weight basis) had significantly higher levels of glycoalkaloids as compared to fresh potato tubers (147.03 mg/kg dry weight basis) (Figure 4.2). This indicate that mechanical damage, light, and fluctuation in temperatures to which tubers are exposed during harvesting, transport, sorting, and during selling substantially increases the level of glycoalkaloids found in tubers immediately after harvesting. These findings corroborate the observations of Musita *et al*. (2018), Haseena *et al*. (2019), Nie *et al*. (2019), Dusza *et al*. (2020), and Rymuza *et al.* (2020), who reported a significant increase in glycoalkaloid content across all tested varieties upon exposure to light, mechanical damage, and elevated storage temperatures.

### 5.8 Effect of common processing methods on pesticide residue levels

Before consumption, potatoes are generally processed through various methods such as boiling, frying, baking, roasting, and steaming. Common cooking methods are characterized by use of temperature variations, duration and moisture loss which affect the pesticide residue levels (Li *et al.,* 2021). High temperatures during the heating process reduce pesticide residue levels, but can also degrade some pesticides into metabolites. In some cases, there might be formation of more toxic by-products or metabolites of pesticides (Han *et al*., 2013a; Kontou *et al.,* 2004; Wu *et al*., 2022) or increase in the residue level of pesticides as a result of the concentration effect (Jiang *et al.,* 2013). Wu *et al*. (2022) identified nine metabolites derived from four pesticides; imidacloprid, diafenthiuron, malathion, and chlorothalonil present in processed green tea. The findings revealed that, compared to the parent pesticides, the total residue levels, including their metabolites, increased by 1.7 to 105.2 times, significantly elevating the acute risk associated with their consumption. Similarly, Bonnechère *et al*. (2012) demonstrated that both household and industrial processing of spinach treated with mancozeb resulted in the production of degradation products, including 3,5-dichloroaniline from iprodione and ethylenethiourea from mancozeb, with sterilization yielding the highest levels of these by-products. Further, Kontou *et al*. (2004) observed that thermal treatment of tomatoes treated with maneb caused significant degradation of the pesticide, with extensive conversion to ethylenethiourea, a compound linked to thyroid toxicity (WHO, 1988). Han *et al*. (2013) investigated the behaviour of chlorpyrifos and its primary metabolite, 3,5,6-trichloro-2-pyridinol (TCP). TCP exhibited toxicity levels two to three times higher than that of chlorpyrifos in developing embryos. These findings emphasize the critical importance of monitoring pesticide metabolites in food, as they pose significant risks to human health and environmental safety.

Frying was most effective for reducing residues of atrazine (78.74%), chlorpyrifos (58.43%), lambda-cyhalothrin (92.37%), and mancozeb (42.75%) while least effective in the reduction of azoxystrobin (16.41%) and fenitrothion (21.28%) when compared to other methods. These differences may be associated with the chemical properties of the pesticides. Pesticides with higher fat solubility (higher log P values) tend to be more readily removed by frying due to their affinity for oil. Additionally, certain pesticides are thermally unstable and break down at high frying temperatures (Phopin *et al*., 2022). Several studies have shown that frying potatoes can lead to reduced levels of pesticides (Soliman 2001; Phopin *et al*., 2022).

A study conducted by Phopin *et al*. (2022) found that boiling was effective in reducing water-soluble pesticide residues by 18-71% in Chinese kale and yard-long beans but demonstrated limitations for removing more lipophilic (fat-soluble) residues. In this study, boiling showed the highest reduction of residues of metolachlor (68.4%), metalaxyl (91.24%), mancozeb (38.44%), fenitrothion residues (73.3%), α-cypermethrin (92.29%), and imidacloprid (42.49%). This is because they have higher water solubility and lower lipophilicity. Therefore, these compounds can efficiently leach out from the potato matrix into surrounding boiling water, facilitating dissipation. Additionally, their chemical structures and functional groups make them less thermally stable at elevated temperatures further accelerating hydrolytic and oxidative degradation. Azoxystrobin was more resistant to boiling with only a 10.56 % reduction, potentially due to its comparatively higher log P and thermal stability (Sandu *et al*., 2014).

Baking had the highest atrazine degradation (48.1%), and λ-cyhalothrin reduction (85.53%). On the other hand, it showed the least effectiveness in reducing 2,4-D residues, with only a 44.38% reduction. This variation in efficacy can be attributed to the impact of high temperatures during baking, which can induce evaporation or thermal degradation processes, thereby leading to a decrease in residues. The dissipation of pesticide residues during cooking is primarily driven by physicochemical mechanisms such as thermal degradation, co-distillation and evaporation all of which are influenced by the chemical properties of the pesticide (Randhawa *et al*., 2014; Zhang *et al*., 2022).

Steaming was efficient for the reduction of fenitrothion (46.72%) and chlorpyrifos (72.72%). However, these results contradict some prior studies. For example, Hanafi *et al.*, (2016) found that steaming Okra led to increased levels of other pesticide residues such as indoxacarb, fenarimol, acetamiprid, and chlorfenapyr. Similar increases with heating have been noted in other studies like Keikotlhaile *et al*. (2010) and Yang *et al.* (2012). The World Health Organization (1997) reports that processing methods can concentrate residues and result in higher levels of food compared to raw commodities. Differences across studies may be attributed to pesticide chemical properties, produce characteristics, and steaming parameters. Pesticides with greater thermal stability could result in residue increases from heating, unlike less stable ones like fenitrothion and chlorpyrifos, which decreased. Additional factors like food matrix also likely influence reactions. More research is essential to clarify the complex dynamics between heating and various pesticide residues.

Roasting was the least effective cooking method for reducing pesticide residues, yielding only a 39.3% reduction in cypermethrin and a 50.42% reduction in λ-cyhalothrin. Imidacloprid residues decreased by just 17.28% under roasting. This lower efficacy is likely attributed to the lower temperatures reaching the produce compared to methods like boiling, steaming, and frying. Additionally, roasting lacks either a heated aqueous phase (as in boiling or steaming) or heated lipids (as in frying) to facilitate the leaching of pesticide residues from produce matrices (Wang *et al*., 2023).

### 5.9 Effect of common processing methods on the glycoalkaloids levels in potatoes

Various processing techniques play a key role in the reduction of glycoalkaloid levels. Frying resulted in the highest decrease of α-chaconine and α-solanine from 200.4 mg/kg to 96.75 mg/kg (a reduction of 51.72%) and 129.38mg/kg to 75.31mg/kg (a reduction of 41.79%) of dry matter respectively while steaming resulted to the least decrease of α-chaconine to 182.10 mg/kg (a reduction of 9.13%) and 121.18 α-solanine mg/kg (a reduction of 6.34%) of dry matter, respectively. Nie *et al*. (2018) studied how temperature and heating duration affect glycoalkaloid content in potato tubers and observed that the degradation of α-chaconine and α-solanine starts to occur at temperatures above 150°C, most likely due to structural alterations in the glycoalkaloids. These findings align with earlier studies that report frying as the most effective method for glycoalkaloid reduction compared to roasting, baking steaming or boiling with reported reductions ranging between 20% and 90% in the final fried potato products (Nie *et al*., 2018; Rytel *et al*., 2015; Rytel *et al*., 2018).

# CHAPTER SIX

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

i. There are poor potato handling practices along the value chain in Nyandarua county.
ii. Poor pesticide application practices and postharvest harvest handling practices result in increased pesticide residues and glycoalkaloids in potato tubers, respectively.
iii. Common potato processing methods reduce some pesticide residues and glycoalkaloid to safe levels for human consumption.

## 6.2 Recommendations

i. Conduct educational initiatives to promote proper potato handling practices within the local potato farming community.
ii. Implementing best practices in potato handling to avoid accumulation of pesticide residues and glycoalkaloids.
iii. Promote safer processing methods to reduce pesticide residues and glycoalkaloids.

## 6.3 Suggestions for further research

i. Determine the pesticide residues exposure levels to the consumers.
ii. Compare the effect of handling practices on pesticide residues and glycoalkaloid levels in different potato cultivars.

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# APPENDICES

## Appendix 1: Consent form for respondents

I am a Master of Science Student in Food Science at Egerton University, Njoro carrying out a study on the influence of handling practices on pesticide residues and glycoalkaloid levels in potato (*Solanum tuberosum* L.) tubers in Nyandarua County, Kenya.

The main aim of this study is to provide information on the potato handling practices in Nyandarua County and their influence on the pesticide residues and glycoalkaloid levels in potato tubers. The information will be key in coming up with appropriate measures for the prevention and control of pesticide residues and glycoalkaloids accumulation along the potato value chain in Kenya. This will very valuable as a basis for consumer health protection as well as environmental conservation. Participation in this study is voluntary and the information will be used for research only. All the responses will be treated with strict confidentiality. Please note that none of your identities will be revealed.

Your cooperation and participation are highly appreciated.

Thank you.

**Please tick where appropriate below;**

I confirm that I have read and understood the information above ☐

I understand that my participation is voluntary ☐

I permit individuals who are part of this study to access any information given ☐

Name of the Respondent…………………………………….

Signature/thumbprint………………     Date………………………………

**Appendix 2: Survey questionnaire for on-farm pesticide application practices**

Code interviewer………………… No…………….

**Biodata of the farmer**

Name…………………………………………………

Gender; male ☐, female ☐

Age ☐

**Survey questionnaire; Assessment of on-farm practices that are risk factors for pesticide residues in potatoes**

Name of the Respondent…………………………………….

Signature/thumbprint………………  Date………………………………

**2. Demographic characteristics of the farmer**

a) Gender; male ☐, female ☐

b) Level of education……………………

**3.Experience in potato farming**

a) Please indicate the size of your farm? …………………………acres

b) How many years have you been farming potatoes? ……………………..

c) Which diseases attack the potato on the farm?

i. …………………………………….

ii. …………………………………….

iii. …………………………………….

iv. ……………………………………..

v. ………………………………………

vi. ………………………………………

d) Which disease is the most challenging to manage, and why?.........................................................................................

e) Which pests commonly attack the potato on your farm? Please list 5 most significant.

i.…………………………………….

ii.…………………………………….

iii.…………………………………….

iv.…………………………………….

v.……………………………………..

f) How do these pests impact your yields?......................................................................................

g) Which weeds mostly grow on potato farms?

i.……………………………………

ii.……………………………………

iii.……………………………………

iv.……………………………………

h) Which methods do you use to manage these pests, diseases and weeds on your farm?...............................................................................

i) Which potato varieties are mostly grown in this area? Specify

i.……………………………………

ii.……………………………………

iii.…………………………………..

j) Which one do you prefer? List up to 3

i.…………………………………

ii.…………………………………

iii.…………………………………

Why do you prefer them? ………………………

**4.Potato pesticides management**

a) Do you use pesticides in potato farming? Yes ☐, No ☐

If yes, how did you know about pesticides for the first time?.........................................................................................................

b) What are the commercial names of the pesticides you use?

i. ……………………………………

ii. ……………………………………

iii. ……………………………………

iv. ……………………………………

v. ……………………………………

vi. ……………………………………

vii. ……………………………………

How did you know that these are the appropriate pesticides to use?...............................................................................................................................

........................................................

c) Where do you purchase pesticides used on your potato farm?.........................................................................

d) Do you know how to apply pesticides in potato farms? Yes ☐, No ☐

If yes, how do you decide which pesticides to apply and the appropriate time to apply?..................................................

If no, from who do you obtain information on how to use pesticides?............................

e) How many times do you apply pesticides on your potato crops from the time you plant to the time you harvest?....................................................

Do you think this frequency is sufficient? Why or why not?...............................................

f) Which application rates do you use when applying pesticides?..............................................................

How do you know they are the correct rates to use?.......................................

g) Do you mix different pesticides before applying them on your potato farms? Yes ☐, No ☐

If yes which ones and what is the reason for mixing?.................................................................

h) What is the last day or time you apply pesticides on the farm?...........................

Why do you wait for this number of days?........................................

**THANK YOU FOR PARTICIPATING IN THIS STUDY**

**Appendix 3: Survey questionnaire for postharvest handling practices along the potato value chain in Nyandarua County**

**Assessment of post-harvest handling practices among actors along the potato value chain in Nyandarua county**

Questionnaire No………………… Code interviewer…………………

**General information**

Name of sub-county……………………………………………………

Name of market…………………………………………………………….

**Biodata of the actor**

Name

Gender; male ☐ female ☐

Age ☐

Level of education; Never attended any school ☐ primary ☐, secondary ☐ or university ☐

**Variety (s) of potatoes sold**

1. ………………………
2. ………………………
3. ……………………….
4. ……………………….
5. Any other……………

**Information on post-harvest handling and storage (please tick where appropriate)**

**Source of potatoes**

Where do you obtain your potato supply?

a) I produce on my own ☐

b) Buying directly from farmer ☐

c) Buy from other traders/retailers (middlemen) ☐

**Time between supply and market**

How long does it take to deliver potatoes from the point of supply to the market? ....................................................................

**Transportation method**

i) How do you transport the potatoes from the source to the market?

Vehicle e.g. lorry, pickup ☐ hand-pulled cart ☐ other (specify) …………………………

ii) If you use a vehicle/hand-pulled cart, what is the design of its back? ☐ Open back ☐ Closed back ☐

**Storage conditions and duration**

How do you usually store potatoes?

a) cool dry place ☐

b) in piles ☐,

c) in a dark room ☐

d) in a room with enough light ☐

How long do you store your potatoes before the next supply?

a) 1-2 weeks ☐

b) 1 month ☐

c) Over one month ☐

d) Other (specify)……………………

Do you take any specific factors into consideration when storing potatoes? Yes ☐, No ☐

If yes above, please specify the factors ………………………………………

Are the potatoes exposed to sunlight? (Observation by the intervewer) Yes ☐, No ☐

Comments based on the above observation

……………………………………………………………………………………………..

**Knowledge and perceptions**

In your opinion what does "greening" in potatoes indicate?.................................

What actions do you take when potatoes show signs of greening / damage?

Do you think consuming "greened" potatoes is harmful to your health? ……………………………

Have you/anyone you know ever felt unwell after consuming 'greened' potatoes? Yes ☐, No ☐

**Additional comments**

………………………………………………………………………

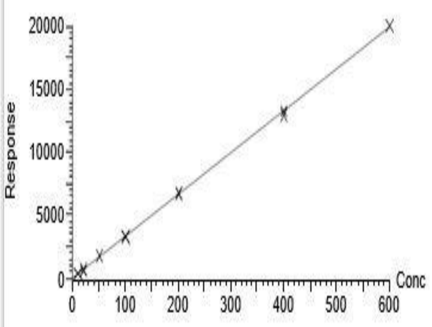
**Appendix 4: Manufacturer's guidelines for the pesticides used by farmers**

| Active Ingredient | Application rates | Frequency of application | Timing | Pre-harvest Interval |
|---|---|---|---|---|
| **Manconzeb and Metalaxyl** | 2.5kgs/ha 50g/20litres of water | 10-14 days with a maximum of 3 applications per season | During tuber development before disease emergence | 7days |
| **α-cypermethrin** | 10ml/20litres of water | 7-14 days | Tuber development when the crop is infected | 3days |
| **Glyphosate** | 1.5 – 2L/Ha | Once | Before planting or during pre-emergence of crop | 70days |
| **Atrazine and Metalochlor** | Should not be applied on potatoes but on maize as per manufacturer's instructions | | | |
| **Imidacloprid** | 500-750 ml/ha in 1000 litres of water | 7–10 days intervals with a maximum 3 applications | After first signs of infestation | 7days |
| **Dichlophenyl Acetic Acid [2,4-D]** | (1.5 – 2.5 Ltr/ ha) | Once | Early post emergence of weeds/Tuber initation stage | |
| **Lambda-cyhalothrin** | 150ml per hectare | Observe a spray interval of 7-10 days. Apply two to three times per season according the population dynamic. Use the shorter spray interval in cases | In case of pest infestation. | 5 days |
| **Deltamethrin** | 5 to 20grams per hectare | 10-14days | In case of pest infestation | 7 days |

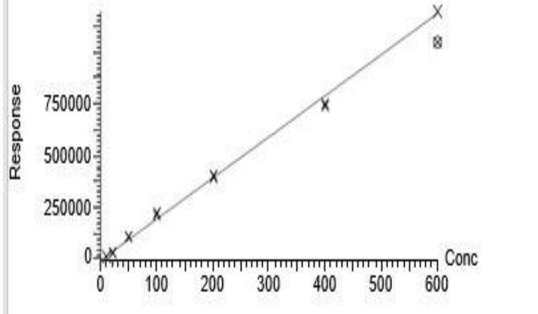
| | | | | |
|---|---|---|---|---|
| **Fenitrothion** | Banned thus no information on use in potatoes | | | |
| **Azoxystrobin** | 0.5 L/ha in 1000 litres of water or 0.5 ml/litre of water | 7-10 days. Do not exceed six applications per season. | After observation of disease | 14 days |
| **Chlopyrifos** | 20-30ml/20l in foliar application and 60-100ml in 20ml in drench application | 7 -14 days with a maximum 3 applications per season | On the soil immediately before planting or during tuber initiation | 21 days |

## Appendix 5: Calibration curves of the pesticide standards

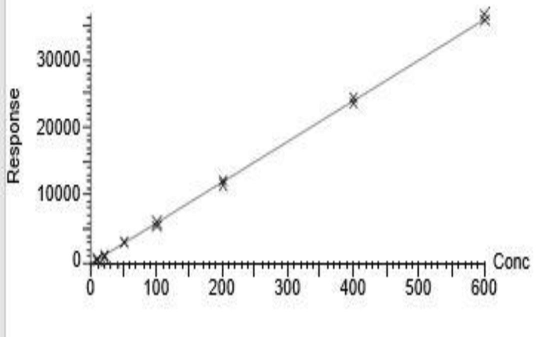
Compound name: 2,4-D
Correlation coefficient: r = 0.999727, r^2 = 0.999454
Calibration curve: 33.2625 * x + -7.99551
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None



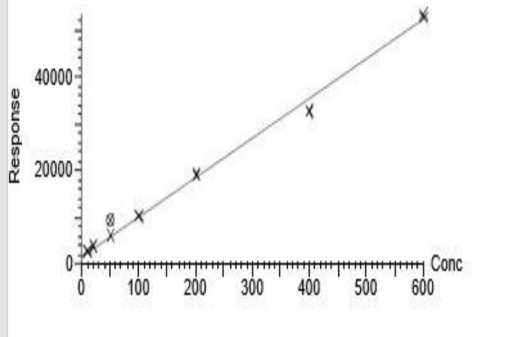

Compound name: Atrazine
Correlation coefficient: r = 0.997347, r^2 = 0.994701
Calibration curve: 1980.37 * x + -2340.49
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None



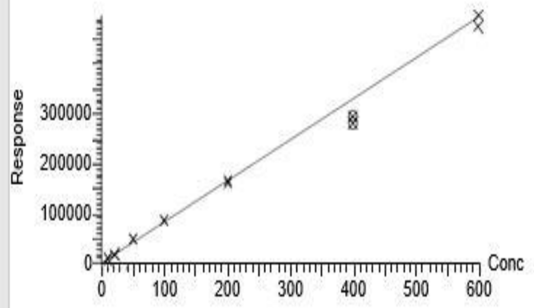

Compound name: Imidacloprid
Correlation coefficient: r = 0.999307, r^2 = 0.998614
Calibration curve: 60.0837 * x + -130.566
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None



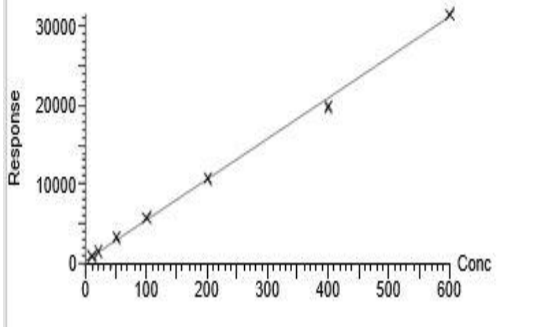

Compound name: Azoxystrobin
Correlation coefficient: r = 0.990391, r^2 = 0.980874
Calibration curve: 85.0596 * x + 1452.87
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None

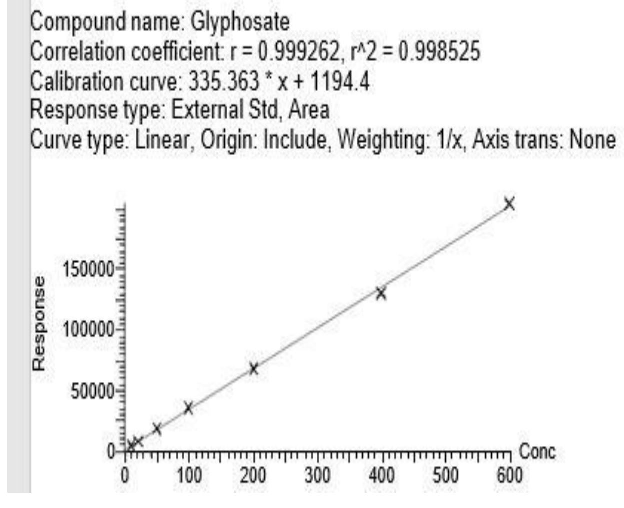


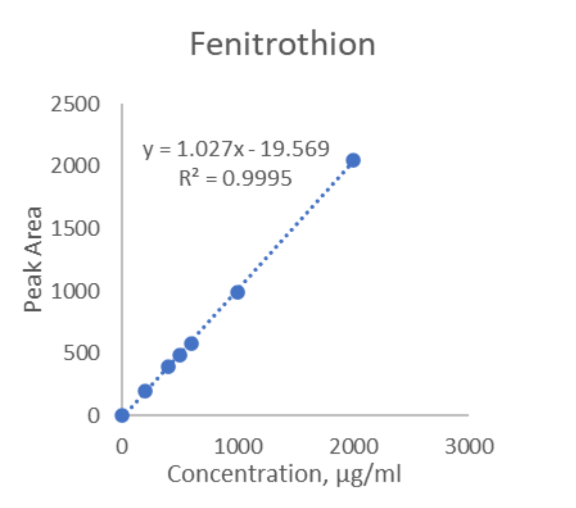

Compound name: Mancozeb
Correlation coefficient: r = 0.998405, r^2 = 0.996812
Calibration curve: 820.225 * x + 2495.25
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None

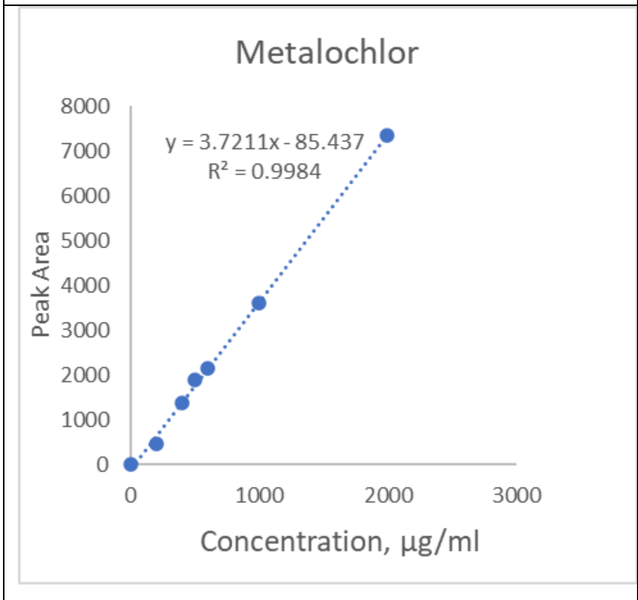


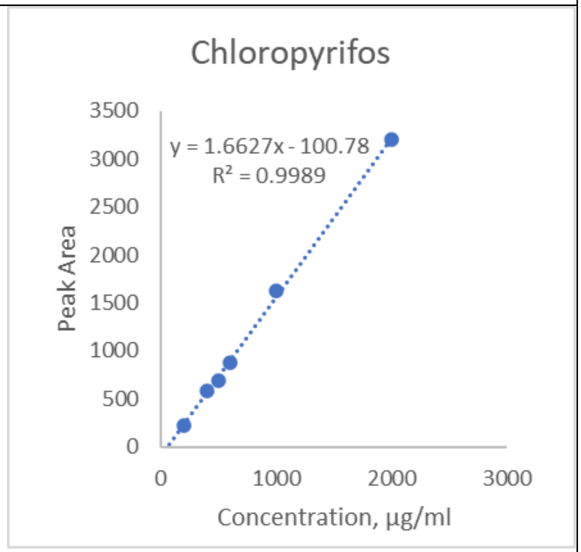

Compound name: Metalaxyl
Correlation coefficient: r = 0.997754, r^2 = 0.995512
Calibration curve: 51.4069 * x + 351.301
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None

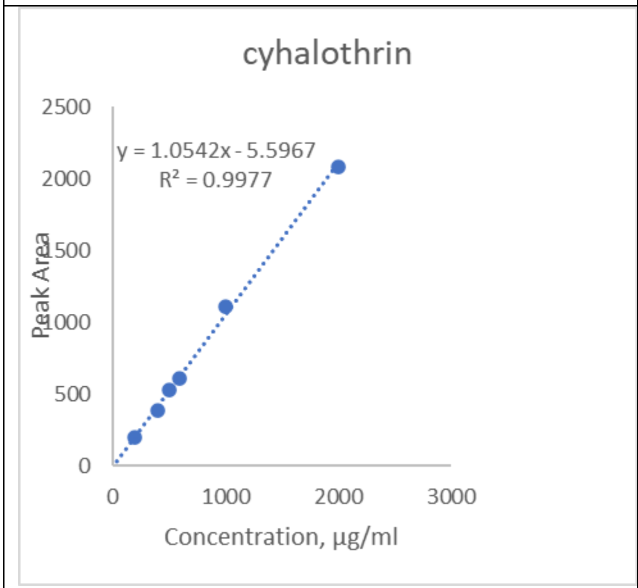


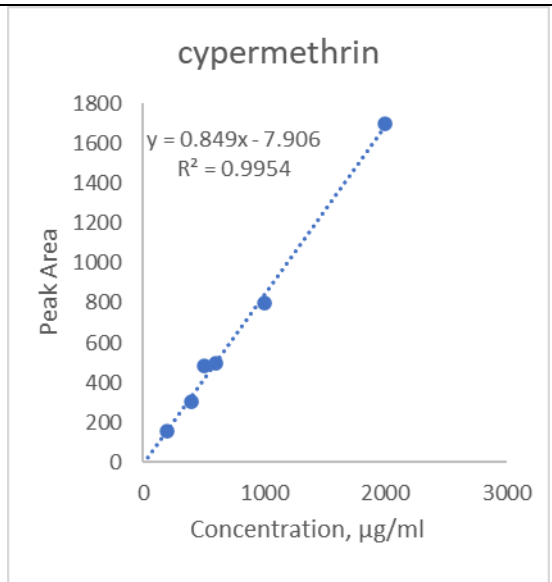

Compound name: Glyphosate
Correlation coefficient: r = 0.999262, r^2 = 0.998525
Calibration curve: 335.363 * x + 1194.4
Response type: External Std, Area
Curve type: Linear, Origin: Include, Weighting: 1/x, Axis trans: None
Response
150000
100000
50000
0
0 100 200 300 400 500 600
Conc


Fenitrothion
y = 1.027x - 19.569
R² = 0.9995
Peak Area
2500
2000
1500
1000
500
0
0 1000 2000 3000
Concentration, µg/ml

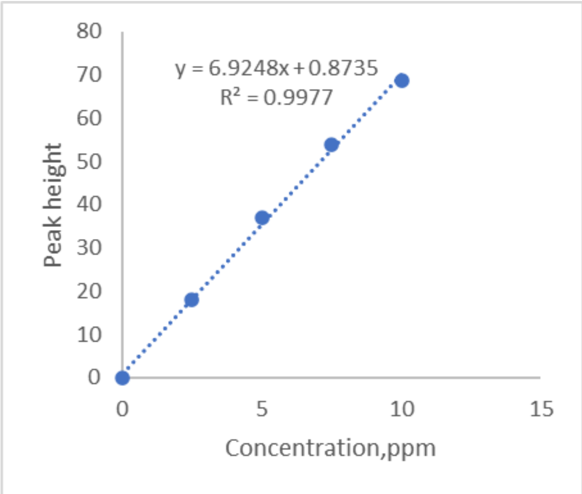
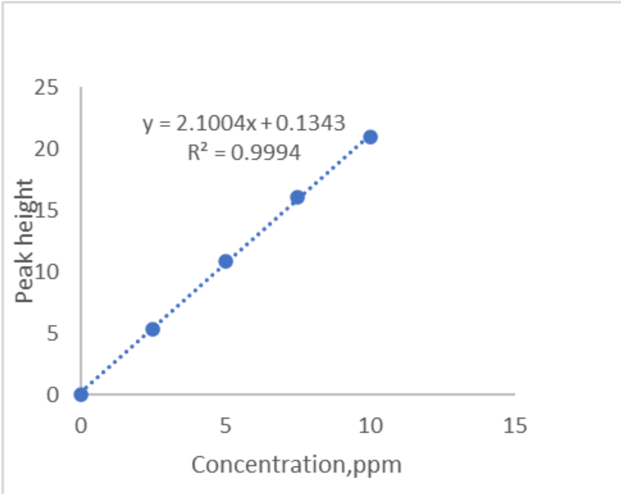

Metalochlor
y = 3.7211x - 85.437
R² = 0.9984
Peak Area
8000
7000
6000
5000
4000
3000
2000
1000
0
0 1000 2000 3000
Concentration, µg/ml


Chloropyrifos
y = 1.6627x - 100.78
R² = 0.9989
Peak Area
3500
3000
2500
2000
1500
1000
500
0
0 1000 2000 3000
Concentration, µg/ml

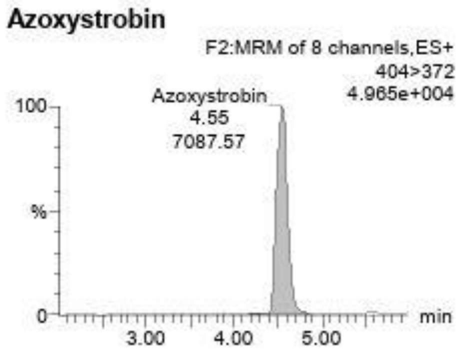

cyhalothrin
y = 1.0542x - 5.5967
R² = 0.9977
Peak Area
2500
2000
1500
1000
500
0
0 1000 2000 3000
Concentration, µg/ml

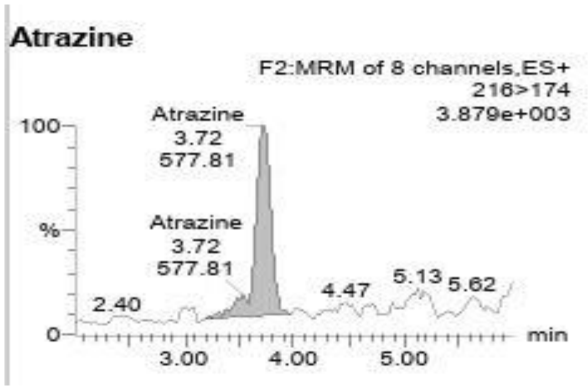

cypermethrin
y = 0.849x - 7.906
R² = 0.9954
Peak Area
1800
1600
1400
1200
1000
800
600
400
200
0
0 1000 2000 3000
Concentration, µg/ml

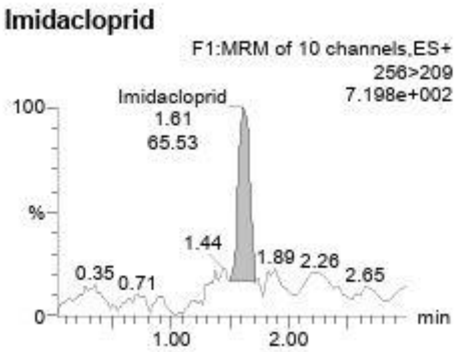
**Appendix 6: Calibration curves of the α-solanine and α-chaconine standards**

| **α-solanine** | **α-chaconine** |
|---|---|
|   |   |

**Appendix 7: Some chromatograms and mass spectra generated from the analysis of the pesticide residues**



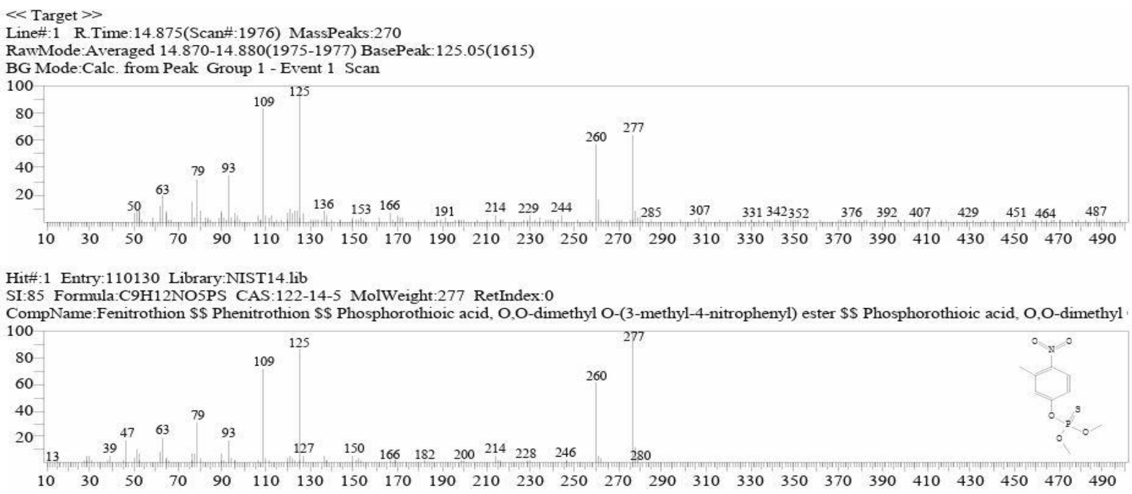



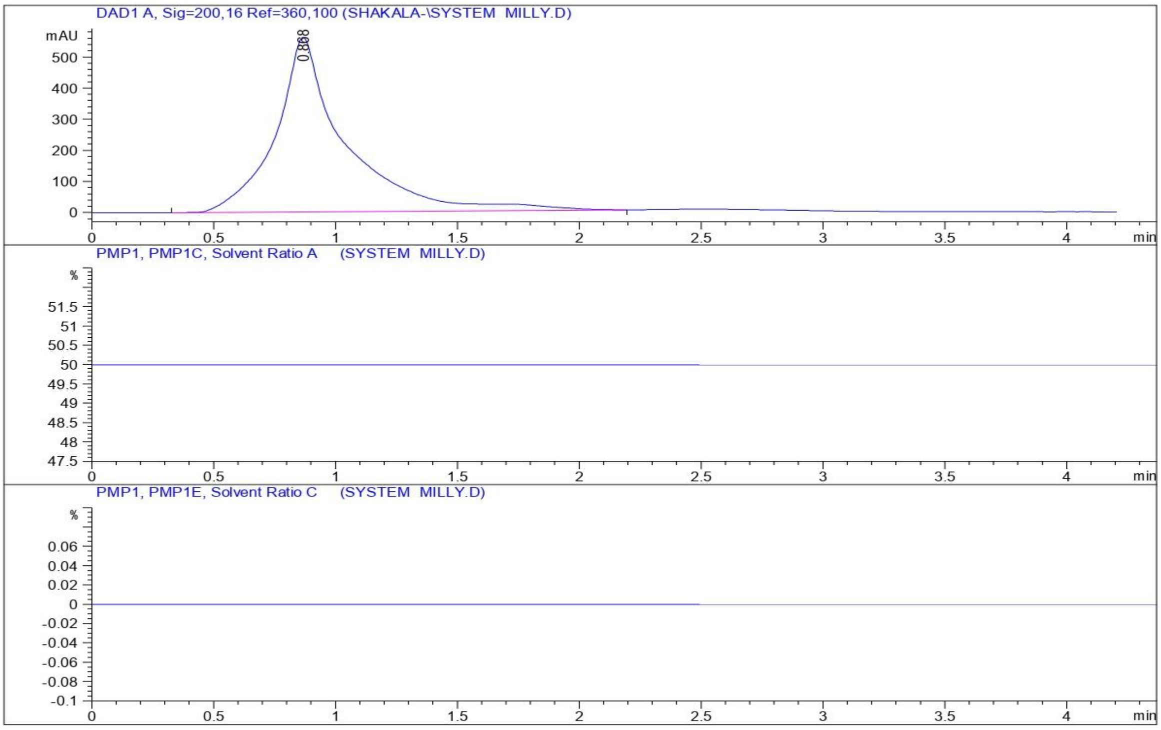

**Figure 5**. Sample Mass spectrum of fenitrothion. Target Line #1 is the spectrum from the injected sample while the Hit #1 spectrum is the library match identifying the target compound as fenitrothion.

# Appendix 8: Some chromatograms generated from the analysis of the glycoalkaloids

```
Data File C:\Chem32\1\Data\SHAKALA-\SYSTEM  MILLY.D
Sample Name: SAMPLE: JMR

    =====================================================================
    Acq. Operator   : SYSTEM
    Sample Operator : SYSTEM
    Acq. Instrument : Agilent LC                    Location :   1
    Injection Date  : 11/21/2023 3:39:04 PM
                                                  Inj Volume : 5.000 µl
    Method          : C:\Chem32\1\Methods\GLYCOALKALOIDS.M
    Last changed    : 11/21/2023 3:11:31 PM by SYSTEM
                      (modified after loading)
    Method Info     : Injection Volume [ 5.0 ], Flow Rate [ 1.500], Column type [DAD], Column
                      Temperature [40], Wave length [ 200-360]Detector [DAD]

    Sample Info     : SAMPLE: JMR
                      MOBILE PHASE A: METHANOL
                      MOBILE PHASE B: ACN
                      COLUMN: 4.6*100mm, C-18, REVERSE PHASE
                      WAVE LENGTH: 230,16 Ref=390,100
```



**Appendix 9: Some of the statistical outputs**

**ANOVA table of mean square errors for the different sources of variation for the different herbicide residues**

| Source of variation | Degree of freedom | 2,4-D | Atrazine | Metolachlor | Glyphosate |
|---|---|---|---|---|---|
| Application rates | 2 | 2.07*** | 4.2*** | 0.32 | 1.57*** |
| Frequency of application | 3 | 43.07*** | 1.35*** | 0.11 | 2.22*** |
| Timing | 1 | 15.2*** | 1.05*** | 0.06 | 1.32*** |
| Preharvest interval | 2 | 2.47*** | 2.35*** | 0.07 | 4.22*** |
| Error | 24 | 0.94 | 0.24 | 0.29 | 0.567 |
| R2 | | 0.939 | 0.9 | 0.892 | 0.892 |
| CV | | 24.756 | 19.125 | 20.736 | 16.247 |

**ANOVA table of mean square errors for the different sources of variation for the different fungicide residues**

| Source of variation | Degree of freedom | Azoxystrobin | Mancozeb | Metalaxyl |
|---|---|---|---|---|
| Mixing pesticides | 1 | 1.07*** | 3.52*** | 2.4*** |
| Application rates | 3 | 1.32*** | 3.92*** | 2.45*** |
| Frequency of application | 3 | 2.57*** | 1.39*** | 4.21*** |
| Timing | 1 | 1.6*** | 2.52*** | 5.27*** |
| Preharvest interval | 2 | 2.45*** | 4.34*** | 3.52*** |
| Error | 18 | 0.94 | 0.35 | 0.29 |
| R2 | | 0.95 | 0.96 | 0.92 |
| CV | | 12.15 | 12.88 | 11.97 |

**ANOVA table of mean square errors for the different sources of variation for the glycoalkaloids**

| Source of variation | Degree of freedom | α-Solanine | α-Chaconine |
|---|---|---|---|
| Fresh tubers | 5 | $0.15^{ns}$ | $2.4^{ns}$ |
| Mechanical Injuries | 5 | 6.05*** | 7.47*** |
| Sprouting | 5 | 7.35*** | 4.2*** |
| Exposure to light | 5 | 5.15*** | 8.87*** |
| Error | 35 | 1.68 | 2.35 |
| $R^2$ | | 0.75 | 0.89 |
| CV | | 18.27 | 14.99 |

## Appendix 10: Research license

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Date of Issue: 12/January/2024

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**Appendix 11: Research Output**

ELSEVIER

Journal of Food Protection

journal homepage: www.elsevier.com/locate/jfp

Research Paper

# Influence of On-farm Pesticide Practices and Processing Methods on Pesticide Residue Levels in Potato Tubers (*Solanum tuberosum* L.) in Nyandarua County, Kenya

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ARTICLE INFO

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On-farm pesticide practices
Pesticide residues
Pesticides
Potato tubers
Processing methods

ABSTRACT

In Kenya, the extensive use of agrochemicals in potato farming raises concerns about pesticide residues in potato tubers and products. This study aimed to document the pesticide application practices of potato farmers in Nyandarua County, Kenya and evaluate the effect of the practices on pesticide residue levels in raw potato tubers. Also, the study evaluated the effect of various heat processing methods on the pesticide residue levels in potatoes. A cross-sectional survey using semi-structured questionnaires was conducted on 275 randomly selected farmers. Alongside, raw *Shangi* potato variety samples ($n = 16$) from respective farmers were analyzed for some of the most commonly used pesticide residues using LC-MS/MS and GC–MS/MS. The study found that 98.8% of farmers use synthetic pesticides, with 96.4% using fungicides, 68.2% insecticides, and 28.7% herbicides. Common fungicides contained mancozeb, metalaxyl, and cymoxanil as the main active ingredients. Insecticides contained α-cypermethrin and imidacloprid, while herbicides had glyphosate and 2,4-D as the main active ingredients. These chemicals were used either alone or in mixtures. Only 11.85% of farmers adhered to the recommended manufacturer's application rates, with the majority relying on advice from agrochemical retailers (74.63%) or other farmers (13.32%). The frequent mixing of pesticides and weekly applications were also common practices. Residue analysis revealed that adherence to the manufacturer's instructions resulted in lower residue levels. Mixing pesticides and frequent applications led to higher residues, particularly for fungicides containing azoxystrobin. Longer preharvest intervals generally reduced residue levels. Most of the pesticide residues were below the EU and Codex Maximum Residue Limits (MRLs) in potatoes, however, the banned insecticides containing chlorpyrifos and fenitrothion were found at levels exceeding the EU and Codex MRLs of 0.01 mg/kg. Processing methods such as frying, baking, boiling, and steaming significantly reduced pesticide residues, below the Codex MRLs. Frying and boiling were particularly effective for most pesticides. However, baking, roasting, and frying were not effective in reducing chlorpyrifos and fenitrothion below EU and Codex MRLs. The findings highlight the need for farmer education on proper pesticide use and adherence to recommended practices to minimize residue levels and ensure food safety.