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ORIGINAL ARTICLE / ORIGINALBEITRAG

Efficacy of the New Herbicide Clomazone Against Weeds in Potato (*Solanum tuberosum* L.), Its Effect On Quality and Its Residues in Tubers and Soil

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Abstract
Weeds represent a main limiting factor in potato production. In this study, the efficacy of clomazone against broadleaf and grass weeds in potato was assessed. Its effect on yield and quality and its residues in tubers and soil were also determined. Two field experiments were conducted on potato cultivar "Spunta" in winter 2020 and 2021. Treatments comprised clomazone sprayed preemergence at 1152 g a.i ha^{-1}, hand hoeing, and unweeded control. Clomazone showed an excellent performance against broadleaf and grass weeds compared to the unweeded and hoed plots. Foliar phytotoxicity symptoms were observed in the potato plants and appeared to negatively affect their growth during the two seasons. The herbicide increased the tuber yield and the sugar and starch contents compared with the untreated control, but to a lower extent than the hoeing treatment. The clomazone residues in soil and tubers were determined using HPLC-DAD. Data revealed that no detectable residues (<0.01 mg.kg^{-1}) of clomazone were found in either tubers or the soil at harvest time. The results suggest that clomazone is a potential alternative herbicide to metribuzin for the effective control of weeds in potato and could be integrated with manual hoeing as a useful tool. However, more research is needed on the safety and efficacy of clomazone under different conditions, in different situations, and in other potato varieties.

Keywords Potato · Clomazone · Weed control · Residues · Yield · Quality

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Wirksamkeit des neuen Herbizids Clomazon gegen Unkräuter in Kartoffeln (*Solanum tuberosum* L.), seine Auswirkungen auf die Qualität und Rückstände in Knollen und Boden

Zusammenfassung

Unkräuter stellen einen der wichtigsten limitierenden Faktoren im Kartoffelanbau dar. In dieser Studie wurde die Wirksamkeit von Clomazon gegen breitblättrige und grasartige Unkräuter in Kartoffeln untersucht. Außerdem wurden seine Auswirkungen auf Ertrag und Qualität sowie seine Rückstände in Knollen und Boden bestimmt. Im Winter 2020 und 2021 wurden zwei Feldversuche mit der Kartoffelsorte „Spunta" durchgeführt. Die Behandlungen umfassten Clomazon, das vor Pflanzenaufgang mit 1152 g a.i. ha^{-1} gespritzt wurde, Handjäten und Kontrolle ohne Unkrautbekämpfung. Clomazon zeigte im Vergleich zu den Pflanzen ohne Unkrautbekämpfung und den handgejäteten Flächen eine hervorragende Wirkung gegen breitblättrige Unkräuter und Gräser. An den Kartoffelpflanzen wurden Phytotoxizitätssymptome auf der Blattoberfläche beobachtet, die ihr Wachstum in beiden Jahren negativ zu beeinflussen schienen. Das Herbizid steigerte den Knollenertrag sowie den Zucker- und Stärkegehalt im Vergleich zur unbehandelten Kontrolle, jedoch in geringerem Maße als beim Handjäten. Die Clomazon-Rückstände in Boden und Knollen wurden mittels HPLC-DAD bestimmt. Die Daten zeigten, dass zum Zeitpunkt der Ernte weder in den Knollen noch im Boden nachweisbare Clomazon-Rückstände ($<0{,}01\,mg.kg^{-1}$) vorhanden waren. Die Ergebnisse deuten darauf hin, dass Clomazon ein potenzielles alternatives Herbizid zu Metribuzin für die wirksame Bekämpfung von Unkräutern in Kartoffeln ist und als nützliches Hilfsmittel mit Handjäten kombiniert werden könnte. Allerdings sind weitere Untersuchungen zur Sicherheit und Wirksamkeit von Clomazon unter verschiedenen Bedingungen, in verschiedenen Situationen und bei anderen Kartoffelsorten erforderlich.

Schlüsselwörter Kartoffel · Clomazon · Unkrautbekämpfung · Rückstände · Ertrag · Qualität

Introduction

Potato (*Solanum tuberosum* L.) is the most important tuber crop worldwide and currently occupies the third place among the most common food crops in the world (Soren et al. 2018). In Egypt, potatoes are the third most significant vegetable produced (European Union 2019). Potato tubers contain valuable nutrients, such as carbohydrates, proteins, and various amino acids (Wichrowska 2022). High yield and better quality are the two major aims in potato production. However, weed infestations are considered one of the main constraints, substantially decreasing potato production. From an economic standpoint, weeds cause the greatest yield losses in crops compared to other pests worldwide (Rao 2000). The loss of tuber yield due to weed competition can reach up to 80% (Ivany 1986; Karimmojeni et al. 2014). Weeds not only compete with the crop for nutrients, soil water, space, and light, but also serve as hosts for several pests and diseases. In addition, weeds can also impair potato tuber quality attributes (Caldiz et al. 2016). The contents of dry matter, starch, and total sugars in potatoes are among the most important quality parameters influencing the suitability of tuber consumption (Zarzecka et al. 2021). Starch is a major component of potato tubers and is linked with the dry matter content (Baranowska and Mystkowska 2019). The total sugar in potato is also indicator of the quality of tubers (Morales-Fernández et al. 2015). Hence, weed control should be performed until the plants properly cover the soil surface, especially during the critical period of growth (Silva et al. 2011).

The application of herbicides, principally at early crop stages, plays a crucial role in reducing weed competition in potato, being the most effective and favored means of weed control. In Egypt, selective herbicides for use in potatoes, mainly for broadleaf weeds, are limited. Metribuzin is the most commonly used herbicide and has been used for numerous years for weed control in potato. However, certain weed species currently are not being controlled effectively, which might be due to the development of herbicide resistant weed species (Ma et al. 2020). Clomazone, which belongs to the isoxazolinonase class, is a new selective pre-emergence herbicide used for controlling annual grass and broadleaf weeds. Clomazone is an inhibitor of chlorophyll and carotenoids biosynthesis in plants. It is absorbed from the soil via plant roots and also taken up through the shoots, then transported via the xylem to leaves, where it diffuses (Scott and Weston 1992; Vencill, 2004). In Egypt, there have been no previous reports on the efficiency of clomazone against potato weeds nor the response of potato to its action. Moreover, there are very limited data on the residues of clomazone in soil (Nalini et al. 2016) and/or in potato tubers. Thus, this work mainly aims to assess the efficacy of clomazone against potato weeds, evaluate its impact on potato yield and quality and determine its residues in tubers and soil at harvest time.

Materials and Methods

Herbicide Efficacy

The field work for this study was carried out at the Agricultural Experimental Station, Giza, Egypt (30° 0′ 47.0016″ N and 31° 12′ 31.8708″ E) during the winter season from November to March 2019–2020 and 2020–2021. The potato cultivar "Spunta" was planted with spacing of 25 cm × 25 cm between plants and 0.7 m between the rows. Soil characteristics at the experimental site are shown in Table 1. The soil characteristics at experimental site are shown in Table 1. The soil analysis was performed at the Laboratory of Soil, Water and Environmental Institute, Agricultural Research Center, as described by Donald (1996). The treatments consisted of clomazone (Moon page 48% EC; StarChem) at the recommended rate of 1152 g a.i ha^{-1}, hand hoeing twice (at 3 and 7 weeks after planting), and the untreated control (without weeding and or herbicide application). The herbicide was sprayed two weeks after potato planting and before plant emergence (preemergence of the crop). The application of the herbicide was based on the instructions specified by the manufacturer. Clomazone was sprayed with an operated knapsack sprayer fitted with a flat fan nozzle using a spray volume of 500 L ha^{-1}. The plot area was 25 m^2, and the experimental plots were arranged in a randomized complete block design with four replicates. Farm management, agricultural practices, and pest control were carried out according to the farm profile. Four weeks after clomazone application, broadleaf and grass weeds were collected randomly from 1 m^2 of each treatment and the efficacy of clomazone was measured according to Yadav et al. (2015) as follows:

$$\text{Weed control}\,\% = (\text{WFWC} - \text{WFWT})/\text{WFWC} \times 100$$

where, WFWC = weed fresh weight in the unweeded control; WFWT = weed fresh weight in treatment. The potato plants were grown until ripening (120 days after planting) and the total yield was determined.

Determination of Photosynthetic Pigments

The calorimetric method of Lichtenthaler and Buschmann (2001) was used to measure the chlorophyll (a and b), and carotenoid contents in fresh leaf tissues.

Vegetative Growth Parameters

The following growth parameters were measured in each treatment: the plant height, shoot fresh and dry weight, and number of stems.

Potato Tuber Yield and Its Components

Tuber weight, dry matter, number of tubers per plant, and the total yield were measured. The dry matter content of the potato tubers was determined using the oven-drying method according to the following equation:

$$\text{Dry matter}\,\% = \text{Dry weight}/\text{Fresh weight} \times 100$$

The total yield of each treatment was calculated by weighting all potato tubers of each treatment after harvesting using a digital balance.

Measurement of Major Tubers' Chemical Constituents

Starch content was calculated according to Burton (1948):

$$\%\text{Starch content} = 17.546 + 199.07(\text{specific gravity} - 1.0988)$$

where specific gravity = tuber fresh weight/tuber volume.

The total soluble sugar content was extracted according to Giannoccaro et al. (2006) and quantified colorimetrically using anthrone-sulfuric acid (Yemm and Willis 1954).

Determination of Clomazone Residues in Tubers and Soil

Sample Collection

Potato tuber samples (~ 2 kg) were taken randomly at harvest time from the treated and untreated plots. Soon after collection, the samples were placed in labeled polyethylene bags and transported in an ice box to the laboratory, where they were kept at 4 °C. Soil samples were also collected at the time of harvesting, in which 2 kg of soil from each replicate were taken from 15 cm deep, before the samples were transported in labeled polyethylene bags to the laboratory. The soil samples were air dried, placed in sealed polyethylene bags, and frozen until analysis.

Table 1 Physical and chemical properties of the experimental soil

Sand (%)	Silt (%)	Clay (%)	Texture	OC	pH (1:2.5)	ECe Ds m^{-1}	O.M (%)	*N* Mg kg^{-1}	*P* Mg kg^{-1}	K Mg kg^{-1}	Fe Mg kg^{-1}	Mn Mg kg^{-1}
25	35	40	Clay loam	0.983	7.820	1.587	0.153	35.720	53.177	494.633	4.797	20.400

Standard Preparation

Stock solution preparation: 1 mg ml^{-1} of a reference standard solution of clomazone purchased from Dr. Ehrenstorfer GmbH (Augsburg, Germany) with a > 97% purity was prepared in acetonitrile, and the stock solution was kept at –18 °C. Mixture standards of 100 µg ml^{-1} of clomazone were prepared by diluting stock solution in acetonitrile. Calibration solutions of 0.01, 0.1, 0.5, 1, 5 and 10 µg ml^{-1} were prepared in acetonitrile.

Extraction Procedure

The QuEChERS method (Anastassiades et al. 2003) was used for herbicide extraction from the potato tubers and soil samples. Whole potato tuber samples were cut with a stainless steel knife using a Hobart Food Chopper (Model: 84181D, Serial: 11-257-552), homogenized, and stored in jars at –20 °C until analysis. Totals of 10 g of potato sample were weighed in 50 ml PFTE tubes, and 3 g soil samples were also weighed, but 7 ml of water was added to 50 ml PFTE tubes. Both tuber and soil samples were subjected to the various procedures and then 10 ml of acetonitrile was added. The buffer-salt mixture (4 g of magnesium sulfate anhydrous, 1 g of sodium chloride, 1 g of trisodium citrate dehydrate, and 0.5 g of disodium hydrogen citrate sesquihydrate) was added and shaken immediately for one minute. Both samples were centrifuged at 5000 rpm for 5 min. A portion of the acetonitrile layer was filtrated using a syringe filter and directly injected into an HPLC apparatus.

HPLC Determination

The High Pressure Liquid Chromatography (HPLC) technique was used to determine clomazone residues. An Agilent HPLC (1260 series) equipped with an analytical column (150 mm × 4.6 mm id, × 5 µm ODS) attached to a photodiode array detector was used. The mobile phase was methanol 70% and water 30%, and the flow rate was 1 ml min^{-1} with an injection volume of 20 µl. The detector wavelength was 205 nm and the retention time was 3.19 min.

Statistical Analysis

Data from the two seasons were combined due to the nonsignificant interaction between the treatments and years for all measured parameters. The treatment methods were compared using the Tukey test (Statistica 7 software; version 7, USA) according to Snedecor and Cochran (1980). Differences were considered significant at α = 0.05.

Results and Discussion

Efficacy of Herbicides

The most predominant broadleaf weed species identified in the two seasons of the experiment were: *Chenopodium album, Sisymbrium irio, Coronopus sp, Cichorium pamilum, Malva parviflora,* and *Sonchus oleraceus.* While the prevalent grass weeds were: *Avena fatua* and *Lolium* sp. The broadleaf weeds germinated primarily early in the season, whereas the grasses germinated later. The preemergence spraying of clomazone on the germinating weeds 28 days after application showed excellent weed control (97.5% and 95.1%) for broadleaf and grass weeds, respectively (Fig. 1). The lowest weed reduction was obtained in the case of hoeing (72.0% and 59.1%) for broadleaf and grass weeds, respectively. However, clomazone injured potato plants during the growing season, causing visible bleaching to the foliage 5 days after emergence. The treated plants showed a little whitening along the leaf veins and edges. As the season progressed, these phytotoxicity symptoms lessened; however, plants appeared to suffer, as slight differences in their foliar growth were observed at harvest.

Very little information is available on the efficacy of the new herbicide, clomazone, against potato weeds, its residues, and its impact on the yield and quality of potato. In Egypt, to the best of our knowledge, this is the first report to investigate such a study. Clomazone caused phytotoxic signs such as leaf bleaching and chlorotic (yellowing) regions which are distinctive symptoms of chlorophyll and carotenoid biosynthesis inhibitors (Vencill 2004; Brunton et al. 2021). However, these symptoms lasted for almost 30 days after emergence and development, until the plants recovered. The application of clomazone, as a selective preemergent herbicide with a new mode of action, facilitates total weed control within plant rows, which may be attributed to the effective elimination of the competition of

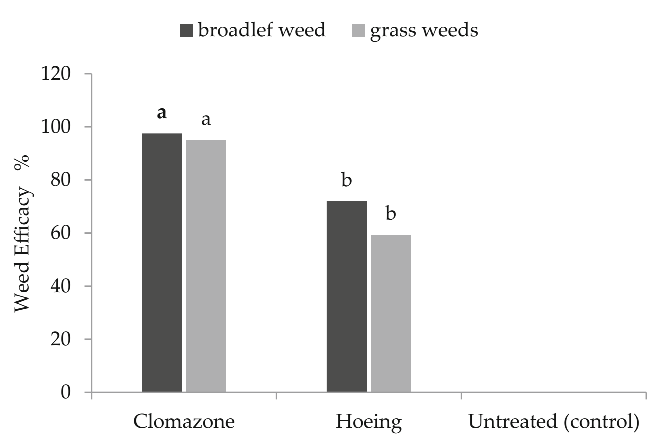

Fig. 1 Efficacy of clomazone against broadleaf and grass weeds in potato

Table 2 Effect of weeds, clomazone and hoeing on photosynthetic pigments in potato

Treatment	Chlorophyll a	Chlorophyll b	Carotenoids
Clomazone	0.18 ± 0.012 b	0.08 ± 0.009 b	0.049 ± 0.006 b
Hoeing	0.29 ± 0.020 a	0.15 ± 0.026 a	0.080 ± 0.003 a
Control	0.16 ± 0.031 c	0.077 ± 0.004 b	0.054 ± 0.004 b

Means within each column followed by the same letter are not statistically different at P ≤ 0.05 according to Tukey Test; ± value indicates standard deviation (± SD) of 4 replicates.

Table 3 Effect of weeds, clomazone and hoeing on vegetative growth of potato

Treatment	Plant length	Shoot fresh weight	Shoot dry weight	Number of stems
Clomazone	57.8 ± 1.4 b	394.39 ± 10.6 b	66.71 ± 1.62 b	6.8 ± 0.19 b
Hoeing	73.5 ± 2.6 a	330.16 ± 10.2 a	51.37 ± 1.12 a	6.3 ± 0.16 b
Control	50.8 ± 1.4 c	116.02 ± 2.47 c	22.08 ± 0.62 c	3.3 ± 0.16 a

Means within each column followed by the same letter are not statistically different at *P* ≤ 0.05 according to Tukey Test, ± value indicates standard deviation (± SD) of 4 replicates.

weeds and the thereby better plant growth (Luz et al. 2018). Clomazone treatment provided season-long control and enabled a larger weed control spectrum, resulting in a greater efficiency than provided by manual hoeing. Our data are supported by Luz et al. 2018, who confirmed the importance of clomazone for controlling certain grass and broadleaf weed species. Our study is also in compliance with reports of other authors, such as Arnold et al. (1997); Gugała and Zarzecka (2013); Hussain et al. (2013); Baranowska et al. (2016). Other studies by Dobozi and Lehoczky (2002) also considered clomazone as a promising pre-emergence herbicide for potato cultivation (Correia and Carvalho 2019). Improving the fresh and dry weight in clomazone-treated plants compared to untreated plants and plants treated with hoeing could also be a result of the effectively reduced interference of weeds allowing potato to utilize its growth resources to gain more dry matter (Shehata et al. 2019).

Photosynthetic Pigments and Carotenoids

No significant differences were detected in the leaf chlorophyll b and carotenoids between clomazone-treated plots and the untreated plots (Table 2). However, a slight but significant difference was found in the chlorophyll a between the herbicide-treated and untreated plots. Hoeing achieved the maximum contents of chlorophyll a and b and carotenoids.

The reduction in photosynthetic pigments determined in potato leaves treated with clomazone may be due to its inhibiting effect on carotenoid biosynthesis (Vencil 2004; Nalini et al. 2016). Herbicides that inhibit carotenoid biosynthesis interfere either directly or indirectly with carotenoid production, protecting chlorophyll from excessive light and photo-oxidation, leading to the destruction of chlorophyll.

Vegetative Growth Traits

The greatest plant length was obtained in the hoeing treatment. However, plants in the clomazone plots accumulated higher fresh and dry weights (Table 3). No statistical difference in the main stem number between the clomazone-treated and hoeing-treated plants was obtained, but the stem number in clomazone plots was two-fold higher than that in the unweeded control.

Our results showed that the fresh and dry shoot weight were decreased in the tested potato cultivars after clomazone application (Dobozi and Lehoczky 2002). Clomazone, fairly and negatively affected certain vegetative parameters via inhibiting the plant height compared to hoeing, as supported by (Luz et al. 2018).

Effect On Tuber Chemical Constituents

As shown in Figs. 2 and 3, significant differences were found between clomazone and untreated control. Clomazone increased starch content and total sugars related to unweeded plots. While, the highest significant increase in

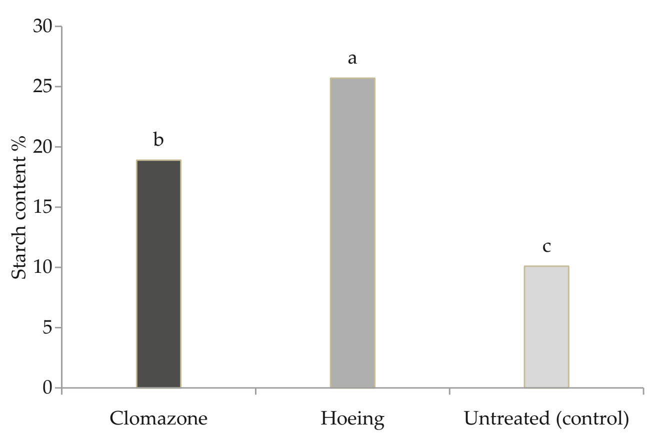

Fig. 2 Effect of clomazone on starch content in potato tubers

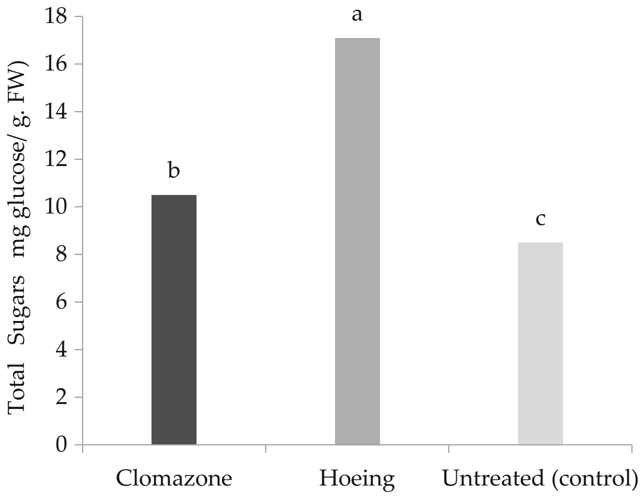

Fig. 3 Effect of clomazone and hoeing on total sugars in potato tubers

both total sugars and starch content (2 and 2.5 times, respectively) was recorded in hoeing treatment.

Regarding the potato quality (total soluble sugars and starch content), a positive effect was obtained in the treated plots compared to the untreated ones. Starch and sugar levels were higher in plots treated with clomazone, which is in line with the findings of Luz et al. (2018). Gugała and Zarzecka (2013) also pointed out that the herbicides increased the total sugars content compared with the untreated control. In the research of Sawicka and Pszczółkowski (2005), herbicides also increased sugars but contributed to a significant reduction in the tuber starch content and dry matter as compared to the hoeing plots. However, Zarzecka et al. (2017) stated that herbicides may elevate or reduce the total sugars level depending on the herbicide type used. They also demonstrated that the total sugars content in potato tubers depended on the weed control method used. Reports from Sawicka and Pszczółkowski (2005) and Baranowska and Mystkowska (2019) stated that tuber's chemical composition, particularly sugar contents depend mainly on meteorological conditions course during potato's vegetation period. Similarly, the high starch yield obtained after the application of the herbicide compared to the untreated control was achieved and confirmed by Zarzecka et al. (2021) and Baranowska (2018). Arora et al. (2009) revealed that the presence of weeds in the untreated plots during the potato growing season decreased the starch content. The application of fluorocloridon, which also blocks carotenoid biosynthesis, exerted a strong negative influence on the tuber quality (Sawicka and Pszczółkowski 2005), as revealed in the current investigation.

Potato Yield and Its Components

The results presented in Table 4 show that clomazone led to a substantial gain in the potato tuber yield, whereas the lowest yield was obtained in the untreated control. However, the yield increase was lower than that recorded in the hoeing treatment. A similar trend was obtained in the case of tuber weight. No significant differences in the number of tubers were found between the clomazone and hoeing treatments, compared to the unweeded control. On the other hand, tubers in the hoeing treatment and the untreated control accumulated significantly more dry weight (20%) than the clomazone-treated plants.

Awan et al. (2010) stated that the potato yield is the most essential factor assessing the treatments applied to a crop for weed management. Thus, our results for yield are consistent with those of Caldiz et al. (2016) and Caldiz and Panelo (1986), who reported that potato yield reduction is commonly due to broadleaf weed competition. The higher tuber yield obtained mainly attributed to the minimum crop-weed competition caused by clomazone at the critical growth period of the crop, which was estimated to be the first 3–4 weeks after planting (Karimmojeni et al. 2014). That would result in favorable conditions for the greater synthesis of carbohydrates and their translocation, as described by Bera et al. (2015). Additionally, Khan et al. (2008) found that the use of different weed management practices can affect the tuber potato yield. Jan et al. (2004) reported a significant increase in potato yield with the use of hand weeding and herbicides over the control, which is in line with our findings. They also found that the unweeded plots were significantly inferior to all the other treatments. The early developed plant injury seemed to have had a harmful effect on the potato plant. Nevertheless, in our study the hoeing treatment provided a significantly higher yield than the clomazone treatment, which could be attributed to the negative impact and intoxication injury potentially caused by the herbicide to the photosynthetic assimilation and transfer process of carbohydrate to the tubers underground (Table 4). The untreated control plots exhibited the lowest tuber yield among all treatments. The potato cultivar "Spunta" may also be susceptible to the

Table 4 Effect of weeds, clomazone and hoeing on potato yield and its components

Treatment	Dry matter (%)	Tuber weight (g)	Number of tuber/plant	Total yield (t.ha^{-1})
Clomazone	30.4 ± 2.7 b	34.1 ± 0.41 b	12.2 ± 1.1 a	28.4 ± 1.2 b
Hoeing	36.87 ± 4.2 a	39.1 ± 0.21 a	12.25 ± 1.26 a	33.3 ± 1.4 a
Control	37.02 ± 3.7 a	25.2 ± 0.21 c	5.00 ± 0.58 b	8.4 ± 1.02 c

Each value is an average of 4 replicates. Means within each column followed by the same letter are not statistically different at $P \leq 0.05$ according to Tukey Test, ± value indicate standard deviation (± SD) of 4 replicates.

Table 5 Recovery percentages of clomazone from potato tubers and soil

Fortified Concentration (μg g^{-1})	Recovery (%) ± SD			
	Tuber	% RSD	Soil	% RSD
0.05	80.48 ± 4.9	5.86	75.04 ± 5.81	5.8
0.5	89.99 ± 5.4	5.41	82.84 ± 1.85	2.0
5	111.68 ± 2.78	2.28	94.22 ± 4.04	5.11

RSD = Replication standard deviation; *Average of 5 replications

tested herbicide, particularly with the higher recommended rate used (1152 g. a.i. ha^{-1}) compared to that described in the literature. Therefore, further knowledge of variety-specific sensitivity is needed, since different varieties may respond differently to herbicides (Lehoczky et al. 2000).

Residues of Clomazone in Soil and Tubers

The recovery experiment conducted showed that the percentage recovery for potato tubers varied from 80 to 111%; however, this value varied between 75 and 94% in the case of soil at a clomazone fortification level from 0.05 to 5 μg g^{-1} (Table 5). The limit of detection and limit of quantification were estimated to be 0.01 and 0.05 mg kg^{-1}, respectively. A calibration curve of the concentration of the clomazone standard injected versus the area observed was plotted. The peak areas obtained from different concentrations of standards were used to calculate a linear regression equation with a correlation coefficient of 0.999, indicating the good linearity and reliable repeatability of the method (Fig. 4). The results showed that no detectable levels of clomazone were found in the analyzed potato tuber and soil samples, as the clomazone residues determined were lower than the detection limit (0.01 ppm).

The determination of herbicide residues in agricultural products has been of worldwide concern for many years due to their potential detrimental impacts on human health and the environment. Information on the presence of clomazone residues in potato tubers or soil is very limited. The data obtained showed, by means of HPLC, there were no detected residues of clomazone in tubers and soil. Our results are supported by other reports (Nalini et al. 2016; Hu et al. 2011) which found no clomazone residues (< 0.01 mg kg^{-1}) in the soil and soybean grains using HPLC-DAD. Additionally, the residues of clomazone in rapeseed plants 22 days after application were also found to be below the maximum residue limits, and clomazone also dissipated very fast in the clay soil used (Szpyrka et al. 2020). Sondhia, (2014) pointed out that clomazone in various commodities was found to be below detectable limits at harvest. There were no traces of clomazone in the root samples of sweet potato at the time of harvesting (Santos et al. 2018). Moreover, Šuk et al. 2021 recommended the preemergent application of clomazone for non-residue carrot production. In contrast, clomazone residues exceeded the detection level in soil and soybean when only applied at a higher dose of 2000 g a.i. ha^{-1} (Nalini et al. 2016). In general, the level of herbicide residues in plants depends on the ability of a given species to accumulate and metabolize the active substance. The weather conditions, rate of application, and formulation type also play an important role. Moreover, the degradation rate and/or persistence of herbicides in the soil depend mainly on the active substance type, its physical and chemical properties, the environmental conditions (soil type, temperature, humidity, pH), and the soil microorganisms, as reported by some researchers (Grygiel et al. 2012; Szpyrka et al. 2020). Nalini et al. 2016 revealed that clomazone is highly polar and slightly to moderately persistent in soils with half life time up to 60 days. Loux et al. (1989) stated that clomazone sorption in soil influences its bioavailability and degradation, which are dependent upon the organic carbon content. They also noted that clomazone generally has a short persistence period in soils (Shaner 2014).

Aekrathok et al. (2021) concluded that plant responses to herbicides depend on the crop variety, age, and the phenological developmental stage of the crop at the application time. The content of starch, as a major component of tubers, has been shown to be related to the herbicide tolerance. Certain crops have an affinity for starch-metabolizing enzymes, which are preserved with this reserve component (Jain et al. 2015; Santos et al. 2018). Although, in the present study, herbicide negatively affects certain growth and quality parameters, the tuber yield increased by 30%, but this rate was

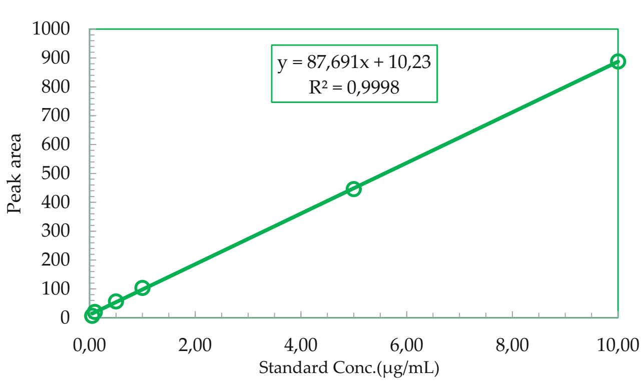

Fig. 4 Calibration curve of clomazone

lower than that in the hoeing treatment. Nevertheless, manual hoeing does not remove weeds within the row and may cause physical damage to potato plants, resulting in more energy being used for stem growth than for tuber growth. Hoeing is also difficult to carry out and time consuming, particularly in large areas and in wide scale farming systems due to the inadequate supply of labor at the proper time and the higher labor operating costs involved (Singh et al. 2013; Soren et al. 2018). In addition, because this requires a lot of man power, it is neither economic nor profitable from the farmer's standpoint (Soren et al. 2018). Strehmel et al. (2010) found that hoeing may cause mechanical damage to plants, which in turn alters their physiological and biochemical relationships. These effects may result from damage to the roots or occur because hoeing spreads weeds that propagate vegetatively. There is also the risk of spreading plant diseases that can penetrate plants through damage caused by hoeing (Castro et al. 2016). In contrast, herbicides can decrease the frequency of cultivation and improve weed control, mostly during the early season before hilling (Chitsaz and Nelson 1983; Nelson and Giles 1989); they also constitute a vital and essential component of weed control and can be a major element of weed management programs (Singh et al. 2007).

Conclusion

In conclusion, weeds in potato should be properly controlled to attain a higher yield and quality. As potato is a crop that is sensitive to the presence of weeds, clomazone, as a new herbicide, has been proven to be an efficient means of controlling broadleaf and grass weeds and achieving a high yield, despite the foliar phytotoxicity that can occur. Hand weeding alone is not effective and should be combined with other control methods in an integrated weed management approach. In addition, clomazone residues in soil and tubers are not detectable at harvest, suggesting that potato tubers can be safely consumed. Nevertheless, our studies suggested that further investigation is needed in order to examine and confirm clomazone weed efficacy and crop safety in potato under different situations and conditions (cultivar, soil type, planting time, planting season, etc.).

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Conflict of interest S.M. El-Ganainy, A.O. Abbas, D. El-Hefny and I.S. Abdallah declare that they have no competing interests.

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