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Research article

Evaluating the effects of manual hoeing and selective herbicides on maize (*Zea mays* L.) productivity and profitability

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ABSTRACT

The objective of this study was to evaluate maize production and the economic profitability of weed management techniques. Field trials were conducted at the Kasapa farm during the 2021/22 growing seasons using a split-plot design with three repetitions. The main factor was the herbicides applied in pre-emergence alone (2L ha^{-1}: acetochlor, bentazon, imazethapyr and 60 g ha^{-1} chlorimuron-ethyl), then mixed (1L ha^{-1}: acetochlor plus bentazon plus imazethapyr plus 30g ha^{-1}chlorimuron-ethyl), manual hoeing (3-5WAS) including the non-weeding. The secondary factor: maize varieties (GV672A, GV673A, GV664A and Sam4vita). The highest maize dry grain yield (7.66 t ha^{-1}) was associated with imazethapyr, while those of acetochlor and chlorimuron-ethyl (6.86 and 6.92 t ha^{-1}) compared to manual hoeing (7.62 t ha^{-1}, respectively) were low, but much higher than no weeding (1.21 t ha^{-1}). The yields of varieties GV672A and GV664A were higher (6.87 and 6.77 t ha^{-1}), compared to Sam4vita (5.64 t ha^{-1}). The total dry weight of weeds was negatively correlated with all crop parameters, with its maximum value (127.56 g m^{-2}) characterizing non-weeding, and the minimum for manual hoeing (18.83 g m^{-2}). The Ratio Cost Value showed that all treatments were profitable: imazethapyr > bentazon > chlorimuron-ethyl > combination > acetochlor > manual hoeing. However, imazethapyr was economically more profitable and could replace manual hoeing when the field to be weeded increases and labor is scarce.

1. Introduction

Maize (*Zea mays* L.), when its dry grains are transformed into flour, constitutes the staple food for the majority of the population living in the Haut-Katanga province. Despite large areas being planted each year, its production remains low and cannot cover the food needs of the population which supplements them through frequent imports from southern African countries, such as: Zambia,

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Zimbabwe and RSA [1].

In Haut-Katanga province, maize cultivation is characterized by low yields, generally averaging around 0.7 t ha^{-1} [1], due to the use of less productive varieties that are not adapted to the region [2], low soil fertility, the impact of diseases (stripe, cercosporiosis, smut) [3], and pests such as the fall armyworm, and then weeds [4]. Weeds compete with the crop for water, light, space, and nutrients [5]. In the absence of the final host, they could serve as intermediate hosts for certain insects and/or spores of pathogenic microorganisms [6]. Maize is susceptible to weed competition from emergence to the 8-leaf stage. Therefore, losses in dry grain yields of the crop are proportional to its duration of exposure to weed competition [7,8].

In Haut-Katanga, weeding among smallholders is done manually with hoes and its effectiveness generally depends on the availability of qualified labor, the stage of weed development, while large-scale farmers use herbicides because they offer advantages in terms of time and cultivated area to be weeded [4]. However, their use require in-depth knowledge of application timing and dose needed to effectively control weeds without damaging the crop [9,10]. In addition, their short and/or long-term effects may affect the lives of other non-target organisms such as humans, animals, pollinating insects, soil decomposers, including surface and groundwater contamination [6].The adoption of a weeding technique should not be limited to the evaluation of the yield obtained, but should also include economic profitability [11].

This study aims to increase maize grain production. To achieve this, we will: (1) Determine which weed management technique, among manual hoeing and herbicides, is likely to increase maize dry grain yield and generate profit; (2) Evaluate the distribution and total dry weight of weeds under manual hoeing and herbicides; (3) Evaluate the combined effects of varieties and weed management techniques on maize production and total weed dry weight.

2. Materials and methods

2.1. Experimental site

The study was conducted in the same field during rainy periods over two cropping seasons, 2020/21 and 2021/22, at the Kasapa farm located at 1249 m altitude, 11°35 ′ 11.6″ south latitude, 027° 24′ 48.1″ east longitude. Four maize varieties were used as organic material (Table 1), while five herbicide formulations were used as non-organic material (Table 2).

2.2. Set-up and implementation of experiments

After plowing and manual harrowing with a hoe, the experiment was set up according to the split-plot design with three repetitions and as primary factor (main plot) was the weeding techniques including: herbicides spread in pre-emergence one day after sowing using a backpack sprayer following the doses mentioned in Table 2, manual hoeing at 3 and 6 weeks after sowing (WAS) of maize and no weeding (Table 2). The secondary factor (subplots) was maize varieties (Table 1).

One seed per hole was sown on December 10 on four 5 m long lines at spacings of 0.75 × 0.25 m with immediate input of 300 kg ha^{-1} NPKS (10-20-10-6) and 200 kg ha^{-1} of urea (46 %) applied 30 days after sowing [14]. At the 6-leaf stage to combat fall armyworm, 200 g ha^{-1} of Emamectin benzoate was uniformly applied in all plots.

Table 1
Varietal characteristics.

Varieties	Maturity	Grain type	Type varietal	Grain color	Yield (t ha^{-1})	Source
V1: GV672A	120–130	Semi dent	Hybrid	Orange yellow	10	[12]
V2: GV673A	120–130	Flint	Hybrid	Orange yellow	10	[12]
V3: GV664A	120–130	Flint	Hybrid	Orange yellow	9	[12]
V4: Sam4vita	120–130	Flint	(OPV)	Orange yellow	3.5–4	[13]

OPV: Open Pollinated Variety; MINAGRI: Ministère National de l'Agriculture.

Table 2
Chemical weeding and manual hoeing.

Treatments	Herbicide family	Activate Ingredient	Rates and Frequencies
No weeding (Non-treated)	–	–	
Hand hoeing (Iron blade attached to wooden handle)	–	–	3 and 6 WAS
Acetochlor	Chloroacetamide	900 g L^{-1}	2 L ha^{-1}
Bentazon	Benzothiadiazole	480 g L^{-1}	2 L ha^{-1}
Chlorimuron-ethyl	Sulphonylurea	25 %	60 g ha^{-1}
Imazethapyr	Imidazolinone	100 g L^{-1}	2 L ha^{-1}
Combination: (Acetochlor + Bentazon + Chlorimuron-ethyl + Imazethapyr)			(1 L ha^{-1}+1 L ha^{-1}+ 30 g ha^{-1}+1 L ha^{-1})

WAS: Weeks After Sowing.

At male flowering, in each plot on the two central lines, 10 plants per line were randomly chosen to determine: total height, leaf chlorophyll level using the Soil Plant Development (SPAD-502 Plus Konica Minolta) meter placed on active leaves [15], and the leaf area was determined using the method described by Ref. [16]. After harvest, the yield was estimated according to the formula of [17]:

$$\text{GY}\left(\text{t ha}^{-1}\right) = [\text{Grain Weight x 10 x }(100\text{-MC}) \ / \ (100\text{-Adjusted MC}) \ / \ (\text{Plot Area})] \quad (1)$$

where grain weight is in kg, MC: represents moisture content (12.5 %), and plot area (m^2).

2.3. Weed sampling

Two quadrats of 0.5 mx 0.5 m were randomly placed in each plot before harvesting the crop. All weeds present were cut at ground level, then dried in an oven at 70 °C for 48 h to a constant weight to determine the total dry weight [7]. The Braun-Blanquet scale was used to determine the weed cover abundance in each quadrat. These data were then converted to percentage cover using a ground cover scale with the following intervals: 0–1, 1–5, 5–10, 10–25, 25–50, 50–75, and 75–100 % [18].

2.4. Statistical analysis

Statistical analysis was performed using R software (version 4.1.2; R Core Team, 2021). The split (split-plot) the function of the “agricolae” package was used to conduct a one-way analysis of variance to evaluate the effects of varieties or weed management techniques on the observed parameters, then two-way factors. The year was considered a random factor due to the uncontrolled action of these components. Tukey’s Honestly Significant Difference (HSD) test was used to compare treatment means at ($P \leq 0.05$) [19,20].

The multivariate analyses included a Pearson correlation analysis performed by the “qgraph” package to study linear correlations between crop parameters and total weed dry weight [7], and the pheatmap function of the pheatmap package was used to create a heatmap representing the hierarchical clustering of weed management practices [21].

2.5. Economic evaluation

The economic analysis of weeding practices was calculated based on the average yield of each treatment for all varieties. It consisted of the ratio of the value of the increase in yield of a treatment different from non-weeding to the total cost of the same treatment (RVC). Total production costs included the cost of land preparation, seeds, manual hoeing, herbicides, basal fertilizer (NPK), top dressing fertilizer (urea), insecticide, packaging, and labor costs for sowing plus the application of fertilizer, herbicides and insecticide (Table 5). Profitability was determined by comparing RVC values, where a value greater than 1 indicates profitability and the value is greater than or equal to 3 indicating excellent profitability [6,22].

$$\text{Yield increment} = \text{Yield of treatment -Yield of }(\text{Unweeded}) \quad (2)$$

$$\text{Value of yield increment }\left(\$\text{ha-}^{1}\right) = \text{Yield increment } * \text{ Maize sale} \quad (3)$$

$$\text{Ratio Cost Value (RVC)} = \frac{\text{Value of Yield increment}}{\text{Total cost}} \quad (4)$$

The average selling price of a ton of maize grain on the local market was estimated at $400 [3].

3. Results

3.1. Weather conditions

In 2020/21 and 2021/22, peak rainfall was recorded in March (323.4–326.78 mm), then it decreased significantly in May (1–1.77 mm). Nevertheless, from December to March, rainfall covered more than half of the monthly days. Temperature showed little variation (Fig. 1).

3.2. Soil properties

The results showed strongly acidic soil with low contents of: organic carbon, organic matter and a low Cation Exchange Capacity (CEC), while available phosphorus content was high and total nitrogen, available potassium was medium (Table 3) [23].

3.3. Crop parameters and total weed dry weight

The significant influence of weeding techniques ($P \leq 0.05$) resulted in low values for all crop parameters under no weeding for which only the dry weight of weeds was higher, unlike that manually weeded plots. Large plants were observed after the application of

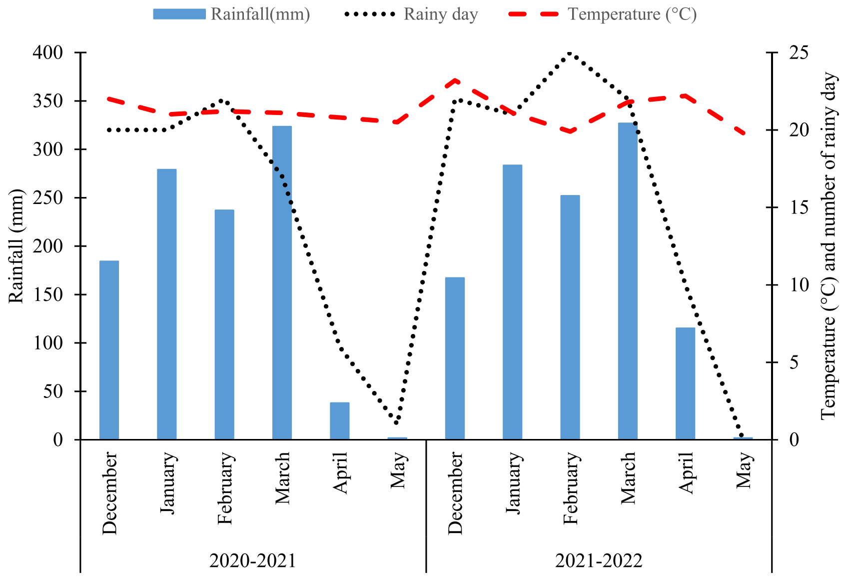

Fig. 1. Weather conditions during 2020/21 and 2021/22 maize cropping season.
Source: Institut National pour l'Etude et la Recherche Agronomiques (INERA) Kipopo

Table 3
Soil chemical properties at the experimental site.

pH (H_2O)	Total nitogen (%)	Available phosphorus (mg kg^{-1})	Available potassium (Cmol kg^{-1})	Organic Carbon (%)	Organic matter (%)	CEC Cmol (+) kg^{-1} soil
5.01	0.09	27.95	0.88	2.56	4.41	6

acetochlor, the large leaf production marked the manually weeded plots. Finally, dry grain yield was higher in plots treated with imazethapyr (Table 4). Significant variety effects ($P \leq 0.05$) were observed on leaf chlorophyll content, with Sam4vita having the highest content and GV672A the lowest. The varieties GV672A and GV664A showed high dry grain production in contrast to Sam 4vita (Table 4).

The combination of two factors generated significant interactions ($P \leq 0.05$) on all parameters studied. Consequently, the responses of each variety varied according to the weeding techniques (Table 4).

3.4. *Economic analysis of weeding techniques*

Total costs were deducted from the fixed costs and variable costs, respectively: plowing plus harrowing \$200, seed plus transport \$60/25 kg, maize sowing plus fertilizer application \$40, whose prices were: NPKS10-20- 10–6 \$55/50 kg bag and urea \$50/50 kg bag plus transport \$10/bag, insecticide \$44.44 plus its application \$20, herbicides spraying \$20.ha^{-1} of which 1 L cost: acetochlor \$12, bentazon \$25, imazethapyr \$25 and chlorimuron-ethyl \$10/60g sachet and manual hoeing \$100 ha^{-1}. For harvesting operations: an empty bag \$0.4/50 kg, destemming plus winnowing \$0.66/50 kg (Table 5).

The results showed that all treatments were profitable with regard to RVC values > 1. However, imazethapyr induced a maximum benefit/cost ratio, while the minimum profitability was recorded under manual weeding hoeing (Table 6).

3.5. *Correlations between variables*

Significant positive correlations (*: $P \leq 0.05$) were observed between Total height and chlorophyll level ($R = 0.51$), yield with chlorophyll content ($R = 50$). Highly significant correlations (**: $P \leq 0.01$) were found between total plant height and leaf area ($R = 0.95$), dry grain yield and leaf area ($R = 90$), leaf area and the chlorophyll content ($R = 0.70$). A highly significant correlation (***: $P \leq 0.001$) was revealed between total height and dry grain yield.

Table 4
Effects of weeding techniques on growth parameters, maize yield and total weed dry weight.

Treatments	Plant height (cm)	Leaf area (cm^2)	Leaf chlorophyll content (SPAD)	Maize grain Yield ($t\ ha^{-1}$)	Total weed dry weight ($g\ m^{-2}$)
Weed management practices					
Acetochlor	179.76 ± 26.24a	526.55 ± 81.50a	35.98 ± 5.98 ab	6.86 ± 0.62c	30.09 ± 14.09BCE
Bentazon	172.44 ± 17.56 ab	523.36 ± 93.10a	35.56 ± 5.34 ab	7.58 ± 1.01 ab	35.84 ± 18.94b
Chlorimuron-ethyl	157.88 ± 23.99BCE	478.31 ± 95.94 ab	36.00 ± 6.37 ab	6.92.03 ± 0.90c	28.10 ± 12.93BCE
Combination	148.03 ± 20.06c	406.64 ± 100.47b	35.78 ± 4.60 ab	7.14 ± 0.84BCE	31.12 ± 18.39BCE
Imazethapyr	167.15 ± 33.84abc	460.84 ± 117.64 ab	34.71 ± 7.87 ab	7.66 ± 1.52a	31.66 ± 19.23BCE
No weeding	92.87 ± 8.86d	265.96 ± 52.33c	29.30 ± 6.29b	1.21 ± 0.08d	127.56 ± 19.93a
Hand hoeing	161.46 ± 24.33abc	447.70 ± 104.80 ab	37.80 ± 6.24a	7.62 ± 1.32 ab	18.83 ± 6.49c
Varieties					
V1	151.25 ± 36.29a	425.04 ± 130.05a	33.33 ± 4.52b	6.87 ± 2.49a	40.77 ± 18.14a
V2	151.52 ± 37.98a	431.85 ± 144.18a	34.54 ± 5.02 ab	6.42 ± 2.31 ab	41.53 ± 11.36a
V3	156.34 ± 31.15a	455.94 ± 122.21a	35.13 ± 8.24 ab	6.77 ± 2.58a	45.70 ± 10.94a
V4	157.80 ± 36.05a	463.95 ± 95.26a	37.07 ± 7.33a	5.64 ± 1.95c	45.26 ± 13.62a
Weed management practices * Varieties					
Acetochlor*V1	189.30 ± 30.41a	547.94 ± 74.38a	31.73 ± 2.41 ab	7.04 ± 0.98abcd	23.50 ± 10.44b
Acetochlor*V2	162.35 ± 22.29 ab	469.58 ± 67.81abcd	32.95 ± 4.52 ab	6.94 ± 0.60abcd	31.72 ± 8.38b
Acetochlor *V3	179.38 ± 11.81 ab	552.87 ± 83.18a	39.76 ± 6.46a	6.49 ± 0.23bcd	33.83 ± 21.06b
Acetochlor *V4	188.01 ± 32.43a	535.82 ± 90.15 ab	39.46 ± 5.70a	6.96 ± 0.43abcd	31.33 ± 14.73b
Bentazon *V1	167.38 ± 21.46 ab	519.52 ± 35.69 ab	32.72 ± 4.15 ab	6.56 ± 0.28bcd	32.48 ± 25.31b
Bentazon*V2	171.99 ± 22.58 ab	543.10 ± 85.77 ab	32.59 ± 5.47 ab	8.73 ± 0.17 ab	32.51 ± 8.57b
Bentazon*V3	176.14 ± 11.73 ab	494.51 ± 71.18abcd	39.42 ± 6.34a	8.34 ± 0.24abc	45.46 ± 23.60b
Bentazon*V4	174.26 ± 16.07 ab	536.30 ± 85.76 ab	37.53 ± 1.10a	6.68 ± 0.17bcd	32.91 ± 15.23b
Chlorimuron-ethyl*V1	146.00 ± 13.69 ab	424.75 ± 78.19abcde	35.91 ± 3.88 ab	7.50 ± 0.25abcd	25.83 ± 10.14b
Chlorimuron-ethyl*V2	152.08 ± 41.21 ab	499.46 ± 22.04abde	36.33 ± 6.51 ab	6.73 ± 0.19bcd	27.33 ± 14.82b
Chlorimuron-ethyl*V3	168.16 ± 14.50 ab	531.60 ± 79.01 ab	35.44 ± 6.42 ab	7.19 ± 0.61abcd	25.40 ± 15.15b
Chlorimuron-ethyl*V4	165.25 ± 12.23 ab	457.42 ± 84.73abcd	36.33 ± 9.36 ab	6.27 ± 0.16cd	33.85 ± 12.71b
Combination*V1	138.72 ± 29.07 ab	341.71 ± 87.59cdef	33.71 ± 3.00 ab	8.38 ± 0.26abc	32.00 ± 19.36b
Combination*V2	147.06 ± 14.38 ab	373.49 ± 01.75bcdef	36.87 ± 4.75 ab	6.51 ± 0.27bcd	21.00 ± 5.83b
Combination*V3	162.19 ± 16.06 ab	425.36 ± 09.94abcde	33.15 ± 4.05 ab	6.54 ± 0.17bcd	29.25 ± 3.22b
Combination*V4	144.13 ± 13.31 ab	486.00 ± 44.38abcd	39.39 ± 4.35a	7.13 ± 0.57abcd	42.25 ± 29.32b
Imazethapyr*V1	168.95 ± 28.90 ab	516.07 ± 99.58abc	28.19 ± 5.45 ab	9.05 ± 0.17a	32.16 ± 14.00b
Imazethapyr*V2	159.15 ± 51.79 ab	406.98 ± 71.96abcde	31.15 ± 3.42 ab	6.69 ± 0.30bcd	21.66 ± 11.23b
Imazethapyr*V3	168.44 ± 25.74 ab	478.96 ± 05.37abcd	39.95 ± 5.96a	9.12 ± 0.41a	29.33 ± 13.53b
Imazethapyr*V4	172.08 ± 31.26 ab	441.35 ± 71.29abcd	39.56 ± 8.97a	5.78 ± 0.19d	43.50 ± 30.01b
No weeding*V1	90.35 ± 9.60b	250.11 ± 37.20ef	34.02 ± 3.10 ab	1.25 ± 0.04e	125.75 ± 7.04a
No weeding*V2	96.40 ± 4.98b	219.27 ± 34.80f	35.33 ± 1.71 ab	1.23 ± 0.10e	138.25 ± 13.48a
No weeding*V3	93.70 ± 9.73b	262.14 ± 32.21f	20.60 ± 0.92b	1.17 ± 0.06e	133.25 ± 33.65a
No weeding*V4	91.06 ± 11.05b	332.33 ± 27.30def	27.23 ± 1.56 ab	1.19 ± 109.43e	113.00 ± 5.44a
Hand hoeing*V1	158.05 ± 17.37 ab	375.14 ± 53.36bcdef	37.02 ± 4.58 ab	8.32 ± 0.22abc	13.66 ± 4.54b
Hand hoeing*V2	171.61 ± 36.64 ab	511.06 ± 17.71abc	36.57 ± 6.29 ab	8.10 ± 0.68abc	18.25 ± 3.54b
Hand hoeing*V3	146.37 ± 11.65 ab	446.14 ± 14.62abcd	37.59 ± 6.36a	8.57 ± 0.20 ab	23.41 ± 9.41b
Hand hoeing*V4	169.82 ± 21.20 ab	458.46 ± 96.99abcd	40.01 ± 8.35a	5.48 ± 0.21d	20.00 ± 3.57b

In each column, means that do not share the same letters are significantly different at $P \leq 0.05$. V1: GV672A, V2: GV673A, V3: 664A and V4: Sam4vita, SPAD: Soil Plant Development.

On the other hand, highly significant negative correlations (**: $P \leq 0.01$) were detected between: total weed dry weight and leaf area ($R = -0.94$), weed dry weight and chlorophyll content ($R = -0.68$), then highly significant between total height and total weed dry weight ($R = -0.96$); dry grain yield and total weed dry weight ($R = -0.97$) (Fig. 2).

3.6. *Effects of weeding techniques on weed species*

The heat map coupled with the dendrogram grouped the weed control techniques into three clusters, the first consisting of no weed control, the second consisting of acetochlor and imazethapyr, and the third consisting of chlorimuron-ethyl and the combination of herbicides. Weed cover varied according to the weeding technique used. In fact, High weed cover was observed with *Commelina*

Table 5
Total production costs for 1 ha of dry maize grain.

Weed control	Cost treatments ($ ha^{-1})	Cost seed ($ ha^{-1})	Labor plus harrowing ($ ha^{-1})	Insecticide plus application ($ ha^{-1})	Sowing more NPK application ($ ha^{-1})	Urea more app ($ ha^{-1})	Cost bags ($ ha^{-1})	Harvest ($ ha^{-1})	Total costs ($ ha^{-1})
No weeding	0	60	200	64.44	430	300	9.67	15.94	1080.05
Hand hoeing	200	60	200	64.44	430	300	60.95	100.57	1415.96
Acetochlor	44	60	200	64.44	430	300	54.86	90.52	1243.82
Bentazon	70	60	200	64.44	430	300	60.63	100.03	1285.09
Chlorimuron-ethyl	30	60	200	64.44	430	300	55.35	91.33	1231.12
Combination	87	60	200	64.44	430	300	57.14	94.27	1292.85
Imazethapyr	70	60	200	64.44	430	300	61.28	101.11	1286.83

Table 6
Economic profitability of weeding techniques in maize cultivation (2020/21 and 2021/22 data pooled).

Weed control	Total costs	Maize sale ($t^{-1})	Yield (t ha^{-1})	Yield increment ($ ha^{-1})	Value of yield increment ($ha^{-1})	Ratio Cost Value (RVC)
No weeding	1080.05	400	1.21			
Hand hoeing	1415.96	400	7.62	6.41	2564.38	1.81
Acetochlor	1243.8	400	6.86	5.65	2259.93	1.82
Bentazon	1285.09	400	7.58	6.37	2548.06	1.98
Chlorimuron-ethyl	1231.12	400	6.92	5.71	2284.32	1.86
Combination	1292.84	400	7.14	5.93	2373.54	1.84
Imazethapyr	1286.83	400	7.66	6.45	2580.73	2.01

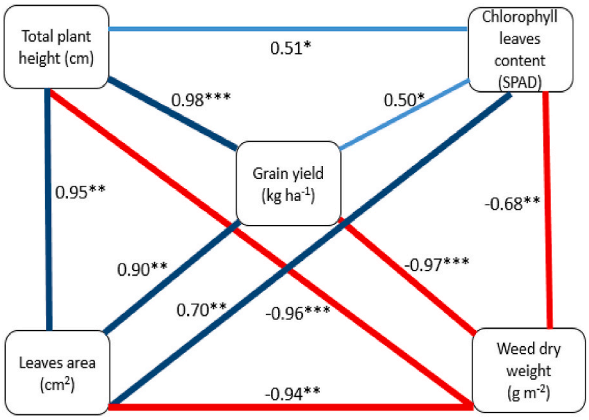

Fig. 2. Pearson correlation coefficients between maize parameters and weed dry weight. Blue and red lines indicate positive and negative correlations. Line thickness is proportional to the strength of the correlation between variables. Stars show the significance level (*: $P \leq 0.05$; **: $P \leq 0.01$ and ***: $P \leq 0.001$), SPAD: Soil Plant Development.

benghalensis, *Cynodon dactylon* and *Imperata cylindrica* (80 %) in the manually weeded plots, *Erigeron bounariensis*, *Ageratum conyzoides*, *Richardia scabra* and *Nicandra physaloides* (80 %) in the unweeded plots, *Bidens oligoflora* and *Spilanthes costata* (75 %) in the plots treated with bentazon, *Centaurea nigra*, *Strobilanthes crossandra* and *Erigeron bounariensis* (60 %) with acetochlor, *Bidens oligoflora*, *Dracocephalon houstonianum* and *Nicandra physaloides* (60 %) after application of imazethapyr, *Nicandra physaloides* (65 %) in plots treated with chlorimuron-ethyl and *Aspilia africana* and *Richardia scabra* (60 %) when herbicides were combined (Fig. 3).

4. Discussion

4.1. Weed dry weight

The results of this study revealed the sensitivity of varieties to long-term weed interference reflected by the negative linear correlations between total weed dry weight and all crop parameters (Fig. 2). The maximum value was recorded in the non-weeded plots (Table 4). This competition significantly reduced the vigor of the maize crop [8,24], negatively affecting growth and/or physiological activities root system. This would have caused nutrient stress [25], and water stress that the plant could overcome by closing the

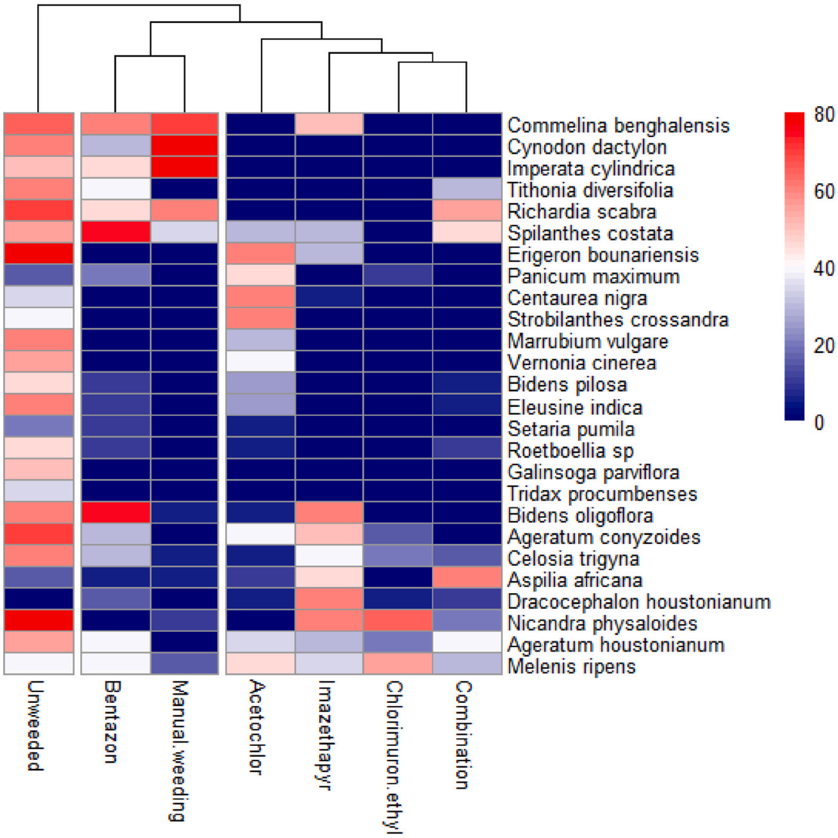

Fig. 3. Heatmap and hierarchical cluster of weed cover species in maize. The highest (80) and lowest (0) values represent the maximum and minimum weed cover, respectively. The heatmap colours code these values from red (maximum) to blue (minimum).

stomata to avoid losing stored water through leaf transpiration. Consequently, leaf chlorophyll content, total height, leaf area, and dry grain yield [26–28].

4.2. Effects of weeding techniques on weed distribution

The associations observed between weed species and herbicides (Fig. 3) show resistance be linked to the existence of one or more resistance genes [29], or a weak residual action of herbicides on late emergences characterizing pre-emergent and pre-sowing modes that inhibit seed germination or disrupt seedling growth and development [30,31].

4.3. Effects of varieties on crop parameters

Variations in leaf chlorophyll content characterizing varieties (Table 4) can be attributed to the horizontal or vertical architecture of leaves on the stem which conditions the perception of incident solar radiation [32,33]. In addition, chlorophyll content is positively correlated with the quantity of nitrogen assimilated by the plant [28]. This claim justifies the maximum value characterizing Sam4vita [34–36], pointed out that most open-pollinated varieties tolerate low soil nitrogen levels while hybrids do not. This ability is an advantage despite the additional input of this element in the form of urea. The height and leaf areas remained similar regardless of the variety (Table 4). Our results suggest that the effects of the environment may have been masked by those of the varieties, although genetically different [2,37].

The greatest yields characterized GV672A, GV673A and GV664A in contrast to Sam4vita (Table 4). According to Ref. [36], these differences are related to the high hybrid vigor of the hybrid varieties but were weak compared to their potential (Table 1). These results could be explained by several environmental factors [2], and biological factors, including armyworm attacks were observed at the 6-leaf stage which interacted with the variety [38]. demonstrated that hybrids are more susceptible than open-pollinated varieties. Consequently, the more the leaves are attacked, the less photosynthates will be accumulated in the seeds [15,39]. Furthermore, the linear correlations observed (Fig. 2) corroborated with the results of the research conducted by Ref. [37] showing the dependence of yield on both morphological, physiological of the variety and environmental factors.

Although the yield of Sam4Vita was lower than the hybrids evaluated, its productivity was higher than the national and regional average (Table 1), and that obtained in South Kivu on nitisol under fractional additions of urea [23]. On the other hand, its average performance was low compared to the results of the study by Ref. [2]. This low productivity would be due not only to the attacks of the fall armyworm observed during the conduct of this study, but also to the sensitivity of the variety to weeds.

4.4. Effects of weeding techniques on crop parameters

No weeding compared to herbicides and manual hoeing resulted in lower values for all crop parameters except total weed dry weight (Table 4). The increase of which would be largely related to the nitrogen applied which would have benefited nitrophilous weeds more than the crop [40,41]. Manual hoeing performed at 3–6 WAS did not reduce maize plant density. However, total height, leaf area and dry grain yield decreased slightly, unlike leaf chlorophyll content (Table 4). This drop in yield, although minimal, would be related to the negative impacts of weeding.

Manual hoeing is widely renowned for its ability to uproot and/or cut weeds [42]. However species such as *Cynodon dactylon*, *Imperata cylindrica* and *Commelina benghalensis* found in our study (Fig. 3) are more difficult to weed manually, and require more energy to destroy their dispersal organs including: rhizomes, stolons, and stems [43], which would have stressed the maize by disturbing the architecture of its root system, thus reducing its ability to take up water and nutrient from the soil [44], thus reducing yield. Similar phenomena have been reported in the same crop in the Czech Republic [45] and more recently in Italy [46]. Added to this stress is the low level of control of the species found in the intra-lines of the culture [47]. Indeed, maize is one of the cereals that has abundant and large foliage. This characteristic combined with the spacing of 0.25 m on the line commonly used in this region [1,3] induced the non-weeding of certain weeds were found on the line. This would have resulted in a reduction in yield due to their competition with the crop, compared to certain herbicides that provided effective weed control. To remedy this situation and increase the dry grain yield of maize [16,42], recommended using herbicides to replace the second manual hoeing. Furthermore, the yield recorded in the manually weeded plots would be linked to the establishment of new roots because the structure of the soil was improved by the hoe passages. This would have favored not only water infiltration, but also the assimilation of other factors and/or elements contributing to plant growth, such as phosphorus, soil temperature [6,48,49]. Furthermore, in this study, urea was not only applied within 45 days as recommended by Ref. [14], but also it was coupled to the second weeding in accordance with the itinerary proposed by Ref. [2]. This resulted in a higher chlorophyll content in the leaves of the plants in this plot compared to the others, thus confirming the results of research having reported an adequate uptake of urea by the culture cleared of weeds [33,50] and thus increase maize yield (Table 4).

As for the effects of herbicides on the dry grain yield of the crop, imazethapyr followed by bentazon then the combination of all the herbicides induced a high yield similar to manual weeding except acetochlor and chlorimuron-ethyl which induced the lowest yields. For this study, the ineffectiveness of acetochlor would be related to the recurring rains that occurred in the days following the spreading (Fig. 1) and then to the low organic matter content (Table 3) characterizing the majority of soils in the Haut-Katanga province [51]. These conditions reduce the adsorption potential of acetochlor to soil colloids and then favor its high accumulation in the rhizosphere [52]. This opinion largely explains the declines in yields were recorded on rice [53,54], then on wheat [55]. [56] insisted on the emulsifiable form which is much more mobile in the rhizosphere than the micro-encapsulated form which cannot become so after disintegration of the envelope sequestering the active ingredient. In disagreement with our results, the application of acetochlor in pre-sowing was able to increase maize yield unlike dimethenamid and rimsulfuron applied respectively in pre-emergence and post-emergence [57]. Partially attesting to our results [5], showed that any increase in acetochlor dose above 1 ppm, i.e. 2, 5, 7.5 and 10 ppm, significantly reduced maize grain yield.

The decrease in maize dry grain yield characterizing chlorimuron-ethyl (Table 4) would be linked to its low degradation in strongly acidic soil (Table 3) which limits the activities and survival of specialized microorganisms such as *Aspergillus niger*, *Streptomyces griseolus*, *Sporobolomyces* sp and *Pseudomonas* sp [58]. In addition, there are added the sensitive differentiation of varieties to herbicides (Table 4) reported on other herbicides by Ref. [59] on nicosulfuron [60], on thifensulfuron-methyl [61], on halosulfuron, then on nicosulfuron, rimsulfuron and foramsulfuron [7]. On the other hand [62], showed an increase in the production of cabbage, sweet potato, tomato and sweet maize sown 12 months after application of chlorimuron-ethyl [63]. had also made this known on maize sown several dozen days after spraying chlorimuron-ethyl or metsulfuron-methyl.

Of all the herbicides studied, imazethapyr, followed by bentazon, are those that best replace acetochlor is widely used in the region [4]. Indeed, the highest yield was induced by imazethapyr, followed by bentazon (Table 4). The highest dry grain yield recorded under imazethapyr would be related to soil acidity, organic matter content and precipitation (Table 3 and Fig. 1), which would have limited its mobility in the soil solution, while increasing its adsorption to soil colloids to promote its biodegradation. In addition, imazethapyr would have less persistence in soil due to phtotodegradation, which occurs beyond biodegradation [64,65]. The results of this research are close to those obtained on the cultivation of maize treated with imazethapyr combined with imazapyr applied at the 6 leaf stage [66]. In the same logic [67], reported increased yield of imidazolinone-resistant maize through the residual effects of imazethapyr combined with imazapic or imazapyr. The effectiveness of these herbicides on post-emergence maize would be due to the fact that these groups of herbicides are selective not only for maize cultivation [9] but also for other straw cereals such as: wheat and rice. On the latter crop, imazethapyr combined with imazapyr does not influence yield regardless of the sensitivity of the crop to this herbicide and the timing of application in non-asphyxiating soil [68]. In certain cases, imazethapyr or herbicides of the same family can induce low yields on maize crops when applied without an antioxidant safener [69] or in submerged rice cultivation whose anaerobic conditions slowed down the biodegradation of imazethapyr, thus accelerating its strong accumulation in the soil solution [70] which can induce other symptoms such as morpho-anatomical deformations of the root system of maize installed in sandy loam soil, slightly alkaline and poor in organic matter [71].

Compared to imazethapyr, the pre-emergence application of bentazon slightly reduced yield (Table 4). Similar results to ours were reported by Ref. [72] on maize varieties less tolerant to bentazon applied at the 5–6 leaf stage. However, the yield induced by this herbicide was greater than that of acetochlor. Indeed, in post-emergence, i.e. two weeks after maize sowing [73], reported an increase in yield. Similarly, in barley [74], noted that bentazon applied alone in post-emergence increased yield, but its combination with imazamox was not beneficial. The increase in yield would be associated to its capacity not only to control weeds but also to persist in the soil for the shortest time following photo degradation, which occurs beyond biodegradation [65].

4.5. Combined effects of weeding techniques and varieties

For the variety-herbicide combination, the results showed a wide range of responses. This variability of responses expresses the tolerance or sensitivity of the varieties used to herbicides (Table 4). Several studies have shown that the response of genotypes differs depending on the herbicide formulation used [63,75]. In this study, the yields obtained in the combinations bentazon x GV672A, acetochlor x GV664A, and combination x GV664A are low compared to the average for each variety. This suggests that GV672A would is sensitive to bentazon, while GV664A is sensitive to acetochlor and the combination of herbicides are under study (Table 4).

4.6. Economic evaluation of weeding techniques

The results of this study demonstrated that in maize cultivation, weed management is very important because it increases productivity and makes it profitable. However, manual hoeing, often applied by the majority of producers in the Lubumbashi region, is less profitable due to the enormous costs involved. Nevertheless [76], had suggested reducing the frequency of weeding when costs are relatively high. This practice may be limited by the impact of the rainy season, and yield would be affected. In such cases, the use of herbicides would be more appropriate, and the results of this research have confirmed the hypotheses of other authors on the importance of herbicides in agriculture [77–79]. Compared to manual hoeing, the use of herbicides has proven to be more cost-effective. In the Lubumbashi region, acetochlor is one of the most used herbicides but its low profitability observed during this study (Table 6) confirms our hypothesis of replacing it with Imazethapyr. In the absence of the latter, bentazon could be used except in GV672A maize fields. The lowest profit was obtained with manual hoeing, despite its higher yield, which did not cover the higher total cost for its implementation.

4.7. Advantages and disadvantages of herbicides and manual weeding

Herbicides are not only economically profitable (Table 6). They also have other benefits such as activating pre-harvest desiccation to reduce the moisture content of seeds in several crops. This facilitates harvesting and reduces the cost of post-harvest drying [80]. In no-till conservation agriculture (CA), herbicides reduce the labor costs involved in opening up the land, then control the established flora and the soil seed bank, which is highly concentrated in the superficial soil horizons [81], they limit the spread of soil-borne phytopathogenic fungi by inhibiting the germination, growth or development of their spores [82]. On the other hand, repeated applications of an herbicide at a non-standard dose and the antagonism between the different active ingredients in the mixture can favor the emergence of "super weeds'' weeds that are very difficult to control [83]. In crop rotations, herbicides that persist for a long period in the soil can induce phytotoxicity to the next crops [84], the plant's poor ability to eliminate herbicide residues from its metabolism may favor their storage in various organs such as fruits, stems, leaves, tubers or seeds, with the risk of contamination of the food chain [85].

In most developing countries, manual weeding owes its popularity to the availability and low-cost acquisition of working tools. In addition, its effects are selective and direct on weeds and not residual in the soil [47], the pressure exerted on the soil by hand weeding improves its structure, facilitating water infiltration and microbial activity [86]. On smallholder farms, weed control is not always carried out at the right time because it is largely dependent on the availability of family labor, which is less costly. This dependence generally results in low crop yields [87].

5. Conclusion

This study highlighted the need for weed control in maize crops to avoid yield losses. The results showed that varieties GV672A, GV673A, and GV664A had better yields than Sam4Vita. The herbicide imazethapyr induced the highest yield, and manual weeding resulted in low weed dry weight. The economic analysis showed that all weed control techniques were profitable, but imazethapyr yielded the most profit, followed by bentazon. It can be concluded that the imazethapyr and bentazon herbicides can substitute manual weeding, which becomes tedious as the field to be weeded grows and skilled labour becomes scarce. Efforts to popularise these herbicides are needed to help farmers overcome the constraints of manual weeding. In addition, certain weeds, such as *Bidens pilosa*, *Nicandra physaloides*, and *Dracocephalon houstonianum*, were not controlled by imazethapyr. Similarly, *Bidens oligoflora*, *Spilanthes costata*, and *Commelina benghalensis* were resistant to bentazon. Although the mechanisms of weed resistance to herbicides were not elucidated in this study, evaluations including the complementary use of these herbicides in post-emergence, the use of an integrated approach combining manual weeding with herbicides can ensure optimal control.

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Data availability

Data will be made available on request.

CRediT authorship contribution statement

Mick Assani Bin Lukangila: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hugues Ilunga Tabu:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Conceptualization. **David Bugeme Mugisho:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Conceptualization. **Antoine Kanyenga Lubobo:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Adrien Kalonji Mbuyi Wa Mbombo:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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