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Two-Pass Weed Management Programs for Identity-Preserved Soybean

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Abstract

Weed management is a challenge in Identity-Preserved (IP) soybean in Ontario, Canada. Six experiments were established in southwestern Ontario, Canada during 2021 and 2022 to evaluate weed control and soybean yield with preemergence (PRE), early postemergence (EPOST), and PRE followed by (fb) late POST (LPOST) herbicide programs. At 8 weeks after LPOST herbicide applications, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE provided 7, 49, and 99% control of velvetleaf; 65, 98, and 100% control of green pigweed; 7, 8, and 82% control of common ragweed; 25, 68, and 98% control of common lambsquarters; 91, 77, and 89% control of barnyardgrass; and 62, 68, and 93% control of green foxtail, respectively. Imazethapyr + bentazon applied EPOST provided 91% control of velvetleaf; 91% control of green pigweed; 78% control of common ragweed; 95% control of common lambsquarters; 76% control of barnyardgrass; and 79% control of green foxtail. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop applied LPOST provided 61, 86, and 100% control of velvetleaf; 97, 99, and 100% control of green pigweed; 94, 88, and 99% control of common ragweed; 96, 98, and 100% control of common lambsquarters; 97, 95, and 97% control of barnyardgrass; and 97, 96, and 99% control of green foxtail, respectively. There was minimal and transient soybean injury (6% or less) with all PRE or EPOST herbicide treatments, however, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST caused up to 22% injury in soybean. Weed interference reduced soybean yield 40%. Weed interference with *S*-metolachlor/metribuzin and pyroxasulfone/sulfentrazone applied PRE reduced soybean yield 25 and 31%, respectively. Reduced weed interference with flumioxazin/metribuzin/imazethapyr applied PRE, imazethapyr + bentazon applied EPOST, and the two-pass programs of a PRE fb LPOST herbicide resulted in soybean yield that was similar to the weed-free control. This study concludes that there are many effective weed management programs in IP soybean; however, the two-pass weed control programs are recommended since they provide good to excellent weed control, minimize soybean yield loss from weed interference, and ensure the use of multiple herbicide modes of action which reduces the selection intensity for the evolution of herbicide-resistant weeds.

Keywords: biomass, density, identity-preserved soybean, two-pass weed control, yield

1. Introduction

Soybean [*Glycine max* (L.) Merr.] (Fabaceae) has been grown in Canada for over 70 years and is currently the third-largest crop grown in Canada (SoyCanada, 2023). In 2020, Canadian growers seeded approximately 2.0 Mha of soybean and produced 6.4 Mt with farm cash receipts of $2.5 billion CAD (SoyCanada, 2023). Almost 4.4 Mt of this production, valued at $2.6 billion was exported to China, USA, Southeast Asia, Europe, and the Middle East while 1.8 Mt was processed in Canada (SoyCanada, 2023). Most of the soybean grown in Canada is produced in Ontario (OMAFRA, 2023). In 2020, soybean growers in Ontario seeded around 1.2 Mha and produced about 3.9 Mt with cash receipts value of approximately $2.0 billion (OMAFRA, 2024).

In the past 30 years, Identity Preserved (IP) soybean production in Canada has been grown by the producers to the customers' specifications (SoyCanada, 2023). Under IP soybean production, growers contract to produce soybean that must meet stringent customer specifications which can include specific cultivars (generally non-genetically modified), specific quality standards, and specialty traits (SoyCanada, 2023). IP soybean production is monitored carefully through every step of production including weed management programs. This begins with stringent production requirements in the field, to storage at the grain elevator, to transport via trucks, rail, and/or ships to ensure IP soybean quality and purity standards are maintained and are traceable back to the producer and seed lots used (SoyCanada, 2023). IP soybean is important to Ontario producers since purchasers pay a premium for this product.

Currently, most of the soybean grown in Ontario is glyphosate-resistant (GR) which has provided soybean producers with efficacious, low-cost weed management (Young et al., 2006; Sikkema & Soltani, 2007; Shurtleff & Aoyagi, 2010; Sikkema et al., 2013); however, glyphosate cannot be used in-crop in IP soybean production. As the number of herbicide-resistant weed biotypes increases across the province and the number of hectares infested expands, the number of viable herbicide options decreases for weed management in IP soybean (Heap, 2023).

Effective weed management is essential for sustainable, long-term IP soybean production in Ontario (Soltani et al., 2017). Herbicide options that can be used for weed control in IP soybean include preplant (PP), preplant incorporated (PPI), preemergence (PRE), early postemergence (EPOST), late postemergence (LPOST), and a sequential application of PP, PPI, or PRE soil-applied herbicides followed by (fb) LPOST herbicide programs. Studies have shown that a single-pass herbicide program can result in weed escapes and poor control of late-emerging weeds (Hartzler, 1996; Loux et al., 2008). The sequential application of a soil-applied herbicide(s) fb LPOST herbicides has the potential to improve weed control in soybean, minimize weed interference, increase soybean yield, and enhance net returns for soybean producers (Hartzler, 1996; Gonzini et al., 1999; Nurse et al., 2007; Loux et al., 2008; Stewart et al., 2011; Underwood et al., 2017). PRE herbicides with potential for weed control in IP soybean in Ontario include *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr. POST herbicides with potential for weed control in IP soybeans in Ontario include imazethapyr + bentazon applied EPOST and bentazon + fomesafen + quizalofop applied LPOST (OMAFRA, 2023).

There is limited information on the efficacy of two-pass weed management strategies for IP soybean where PRE residual herbicides are followed by LPOST herbicides under Ontario environmental conditions. The objective of this research is to evaluate *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE; imazethapyr + bentazon applied EPOST; and sequential applications of *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop applied LPOST for weed management in IP soybean production.

2. Materials and Methods

A total of six experiments were established at the Huron Research Station, Exeter, Ontario and at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario during 2021 and 2022. The soils ranged from Fox sandy loam to Brookston clay loam with 33-82% sand, 5-41% silt, 15-29% clay, 12-33% organic matter, and pH of 6.0-7.9. Site preparation included moldboard plowing in the autumn followed by two passes with a field cultivator with rolling basket harrows in the spring.

Experiments were arranged in a randomized complete block design with four replicates. There were a total of nine treatments as listed in Tables 1-7. Herbicide application doses and adjuvants selected were based on the manufacturers' recommended dose and adjuvant for each herbicide in Ontario.

All plots were 3 m (4 soybean rows spaced 75 cm apart) wide and 8 m long at Ridgetown and 10 m long at Exeter. Soybean seeds were seeded at a density of approximately 400,000 seeds per ha^{-1}. Herbicides were applied using a CO_2-pressurized sprayer calibrated to deliver 200 L per ha^{-1} aqueous solution at 210 kPa. The boom was 1.5 m wide with four ultra-low drift nozzles (ULD120-02, Hypro, New Brighton, MN) spaced 50 cm apart producing a spray width of 2.0 m. PRE herbicides were applied 0-7 days after seeding, EPOST treatments were applied when weeds were up to 2.5 cm in height, and LPOST herbicides were applied when weed escapes were up to 5 cm in height and prior to V5 soybean.

Soybean injury was evaluated visually 2 weeks after emergence (WAE) and 1 and 4 weeks after LPOST herbicide treatment (WAT), using a scale of 0 to 100% where a rating of 0 was defined as no visible soybean injury and a rating of 100 was defined as total soybean necrosis. Percent weed control was visually assessed 2 WAE, and 4 and 8 weeks after the LPOST herbicide treatment (WAT) using a scale of 0 to 100% where a rating of 0 was defined as no weed control and a rating of 100 was defined as complete control. Weed density and biomass (shoot dry weight) were evaluated at approximately 8 WAT by counting the weeds by species and cutting plants at the soil surface in two 0.25 m^2 quadrats per plot and separating by species. Plants were dried at

60 ^{o}C to a constant moisture and then weighed. Soybean was harvested with a small-plot combine at crop maturity and moisture content and weight were recorded. Soybean yield was adjusted to 13% moisture prior to analysis.

The GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC) was utilized for data analysis and the chosen level of significance was 0.05. For the generalized linear mixed model, herbicide treatment was the fixed effect, and environment, environment by treatment interaction, and replicate within environment were the random effects. Soybean yield was analyzed using a Gaussian distribution and visible percent soybean injury and percent weed control were arcsine square root transformed prior to analysis using a Gaussian distribution. Weed density and dry biomass were analyzed using a lognormal distribution. Differences among least-square means were subjected to Tukey's adjustment. Contrasts comparing the overall differences among application timings were also generated.

3. Results and Discussion

The dominant weed species in this study were velvetleaf (*Abutilon theophrasti* Medic.; ABUTH); green pigweed (*Amaranthus palmeri* Wats.; AMAPO), common ragweed (*Ambrosia artemisiifolia* L.; AMBEL), common lambsquarters (*Chenopdium album* L.; CHEAL); barnyardgrass (*Echinochloa crusgalli*; ECHCG), and green foxtail (*Setaria viridis* L.; SETVI). There was no significant interaction between environments and treatments, therefore data were pooled and averaged over environments.

3.1 Soybean Injury and Yield

At 2 WAE, flumioxazin/metribuzin/imazethapyr applied PRE caused up to 6% soybean injury (Table 1). At 1 and 4 weeks after LPOST herbicide application, the PRE herbicides caused no soybean injury. Imazethapyr + bentazon applied EPOST caused 3 and 1% soybean injury at 1 and 4 WAT, respectively (Table 1). However, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST caused up to 20, 20, and 22% soybean injury, respectively (Table 1). Orthogonal contrasts indicated that there was 3% greater injury with EPOST treatments in comparison to PRE treatments at 1 WAT, but the difference was not significant at 4 WAT (Table 1). At 1 and 4 WAT, the PRE fb LPOST treatments caused 21 and 20% greater soybean injury in comparison to the PRE herbicide applications. Similarly, the PRE fb LPOST treatments caused 18 and 19% greater soybean injury in comparison to the EPOST herbicide application at 1 and 4 WAT, respectively (Table 1).

Table 1. Percent soybean injury and yield for soybean treated with a PRE, EPOST or 2-pass herbicide programs at Exeter, Ontario in 2021 (n = 1) and Ridgetown, Ontario in 2021 and 2022 (n = 5) [a]

Herbicide treatment	Rate	Timing	Soybean injury [b]			Yield
			2 WAE	1 WAT	4 WAT	
	g ai ha^{-1}		----------------	%	----------------	T ha^{-1}
Weed-free control			0.0 a	0 a	0 a	3.7 a
Non-treated control			0.0 a	0 a	0 a	2.2 c
S-metolachlor/metribuzin	1943	PRE	0.6 ab	0 a	0 a	2.8 bc
Pyroxasulfone/sulfentrazone	300	PRE	0.1 ab	0 a	0 a	2.6 c
Flumi/metribuzin/imazethapyr	630	PRE	5.6 b	0 a	0 a	3.3 ab
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	3 b	1 a	3.5 a
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	20 c	20 b	3.3 ab
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	20 c	20 b	3.3 ab
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	22 c	21 b	3.5 a
Contrasts						
PRE vs EPOST			-	0 vs 3**	0 vs 1	2.87 vs 3.47**
PRE vs 2-pass			-	0 vs 21**	0 vs 20**	2.87 vs 3.37**
EPOST vs 2-pass			-	3 vs 21**	1 vs 20**	3.37 vs 3.47

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at $P < 0.05$.

* and ** denote significance at $P < 0.05$ and $P < 0.001$, respectively.

[a] Abbreviations: Bent, bentazon; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

[b] No injury observed at 2 WAE and 4 WAT for all sites in 2021, and at 1 WAT for one site in 2021; data not included in analysis due to zero variance.

In other studies, chlorimuron + flumioxazin fb glyphosate (PRE fb LPOST); *S*-metolachlor + metribuzin fb glyphosate (PRE fb LPOST); *S*-metolachlor/metribuzin fb glyphosate (PRE fb LPOST); flumioxazin fb glyphosate (PRE fb LPOST); and pyroxasulfone + flumioxazin fb glyphosate (PRE fb LPOST) caused 4, 2, 2, 4, and 7% soybean injury, respectively (Soltani et al., 2014). Other studies have also shown minimal and transient soybean injury with PP/PRE application of herbicides such as pyroxasulfone + flumioxazin or *S*-metolachlor/metribuzin (Mahoney et al., 2014; Refsell et al., 2009; Underwood et al., 2017; Young et al. 2010).

Weed interference reduced soybean yield 40% (Table 1). Weed interference with *S*-metolachlor/metribuzin and pyroxasulfone/sulfentrazone applied PRE treatments reduced soybean yield 25 and 31%, respectively. Reduced weed interference with flumioxazin/metribuzin/imazethapyr applied PRE, imazethapyr + bentazon applied EPOST, and the two-pass programs of a PRE fb LPOST herbicide resulted in soybean yield that was similar to the weed-free control. Orthogonal contrasts indicated that soybean yield was 17% lower with PRE treatments in comparison to the EPOST treatment. Similarly, soybean yield was 15% lower with the PRE herbicides in comparison to the two-pass (PRE fb LPOST) herbicide applications. There was no difference in soybean yield between the EPOST and two-pass (PRE fb POST) herbicide applications. In other studies, weed interference reduced GR soybean yield 25% (Soltani et al., 2014). The same study showed that soybean yield was lower than the sequential application of glyphosate with chlorimuron or pyroxasulfone/flumioxazin fb glyphosate (Soltani et al., 2014). Another study reported lower soybean yield with PRE application of pyroxasulfone/flumioxazin, flumioxazin, pyroxasulfone, *S*-metolachlor + metribuzin, flumioxazin + imazethapyr + metribuzin, dimethenamid-p + imazethapyr + metribuzin, and *S*-metholachlor + metribuzin + chlorimuron compared to the weed-free control (Mahoney et al., 2014). In another manuscript, there was no reduction in GR soybean yield compared to weed-free control with the sequential application of PRE herbicides such as imazethapyr, *S*-metolachlor + metribuzin and flumetsulam/*S*-metolachlor followed by an application of glyphosate LPOST (Stewart et al., 2011).

3.2 Velvetleaf Control

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled velvetleaf 27, 78 and 98%, respectively (Table 2).

Table 2. Percent control, density and dry biomass of ABUTH treated with a PRE, EPOST or 2-pass herbicide programs at Ridgetown, Ontario in 2021 and 2022 (n = 4) [a]

Herbicide treatment	Rate	Timing	ABUTH control			ABUTH density	ABUTH dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		----------------- % ----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0.0 a	0.0 a
Non-treated control			0 c	0 e	0 e	10.5 d	21.2 d
S-metolachlor/metribuzin	1943	PRE	27 b	10 d	7 d	6.0 cd	20.6 cd
Pyroxasulfone/sulfentrazone	300	PRE	78 ab	52 c	49 c	4.6 bcd	5.9 bc
Flumi/metribuzin/imazethapyr	630	PRE	98 a	99 ab	99 a	0.9 ab	0.3 ab
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	93 ab	91 ab	1.7 bc	0.1 ab
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	72 bc	61 bc	3.2 bc	3.6 b
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	90 abc	86 abc	2.7 bc	3.0 b
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	100 a	100 a	0.5 ab	0.0 ab
Contrasts							
PRE vs EPOST			-	59 vs 93*	55 vs 91**	3.9 vs 1.7	8.9 vs 0.1**
PRE vs 2-pass			-	59 vs 91**	55 vs 87**	3.9 vs 2.1	8.9 vs 2.2*
EPOST vs 2-pass			-	93 vs 91	91 vs 87	1.7 vs 2.1	0.1 vs 2.2

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

[a] Abbreviations: ABUTH, velvetleaf; Bent, bentazon; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and 8 weeks after LPOST herbicide applications, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE controlled velvetleaf 7-10%, 49-52%, and 99%, respectively (Table 2). Imazethapyr + bentazon applied EPOST provided 91-93% control of velvetleaf. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST controlled velvetleaf 61-72%, 86-90%, and 100%, respectively (Table 2). Orthogonal contrasts indicated that there was 34 and 36% greater control of velvetleaf with the EPOST treatment in comparison to PRE treatments at 4 and 8 weeks after LPOST herbicide application, respectively (Table 2). The PRE fb LPOST treatments provided 32% greater control of velvetleaf in comparison to the PRE herbicide applications alone (Table 2). There was no difference in velvetleaf control between EPOST and PRE fb LPOST treatments (Table 2).

S-metolachlor/metribuzin, or pyroxasulfone/sulfentrazone applied PRE did not reduce velvetleaf density but flumioxazin/metribuzin/imazethapyr applied PRE reduced velvetleaf density 91% (Table 2). Imazethapyr + bentazon applied EPOST reduced velvetleaf density 84% (Table 2). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced velvetleaf density 70, 74, and 95%, respectively (Table 2). Orthogonal contrasts indicated that there was no significant difference in velvetleaf density between PRE vs EPOST, PRE vs two-pass, and EPOST vs two-pass treatments (Table 2).

S-metolachlor/metribuzin applied PRE did not reduce velvetleaf biomass but pyroxasulfone/sulfentrazone and flumioxazin/metribuzin/imazethapyr applied PRE reduced velvetleaf biomass 72 and 99%, respectively (Table 2). Imazethapyr + bentazon applied EPOST reduced velvetleaf biomass 100% (Table 2). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced velvetleaf biomass 83, 86, and 100%, respectively (Table 2). Orthogonal contrasts indicated that velvetleaf biomass was reduced 99% greater with EPOST and 75% greater with 2-pass treatments compared to the PRE treatments alone, respectively. However, there was no significant difference in velvetleaf biomass between EPOST vs two-pass treatments (Table 2).

Results are similar to other studies that have shown that two-pass programs of PRE herbicides such as imazethapyr, *S*-metolachlor + metribuzin, or flumetsulam/*S*-metolachlor followed by an application of glyphosate LPOST provided 78-100% control of velvetleaf in GR soybean (Stewart et al., 2011). In another study, the sequential application of a PRE herbicide followed by an application of glyphosate LPOST controlled velvetleaf 99-100% (Soltani et al., 2014). Gonzini et al. (1999) reported 13-22% and 17-27% increase in velvetleaf control compared to a single application of glyphosate when PRE herbicides such as chlorimuron + metribuzin, cloransulam-methyl, or sulfentrazone were followed by glyphosate or sequential applications of glyphosate were applied, respectively.

3.3 Green Pigweed

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled green pigweed 99-100% (Table 3).

Table 3. Percent control, density and dry biomass for AMAPO treated with a PRE, EPOST or 2-pass herbicide programs at Ridgetown, Ontario in 2021 and 2022 (n = 3) [a]

Herbicide treatment	Rate	Timing	AMAPO control			AMAPO density	AMAPO dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		---------------- % ----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0.0 a	0.0 a
Non-treated control			0 b	0 c	0 c	12.1 c	8.9 c
S-metolachlor/metribuzin	1943	PRE	99 a	70 b	65 b	2.1 b	2.6 bc
Pyroxasulfone/sulfentrazone	300	PRE	99 a	98 a	98 a	0.5 ab	0.7 ab
Flumi/metribuzin/imazethapyr	630	PRE	100 a	100 a	100 a	0.0 a	0.0 a
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	91 ab	91 ab	1.3 b	1.2 b
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	99 a	97 a	0.2 ab	0.2 ab
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	99 a	99 a	0.1 ab	0.1 ab
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	100 a	100 a	0.0 a	0.0 a
Contrasts							
PRE vs EPOST			-	94 vs 91	93 vs 91	0.9 vs 1.3	1.1 vs 1.2
PRE vs 2-pass			-	94 vs 100*	93 vs 99*	0.9 vs 0.1*	1.1 vs 0.1*
EPOST vs 2-pass			-	91 vs 100*	91 vs 99*	1.3 vs 0.1*	1.2 vs 0.1*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at $P < 0.05$.

* and ** denote significance at $P < 0.05$ and $P < 0.001$, respectively.

[a] Abbreviations: AMAPO, green pigweed; Bent, bentazon; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and WAT, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled green pigweed 65-70, 98, and 100%, respectively (Table 3). Imazethapyr + bentazon applied EPOST provided 91% control of green pigweed at 4 and 8 WAT. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen +

quizalofop LPOST controlled green pigweed 97-99, 99, and 100%, respectively (Table 3). Orthogonal contrasts indicated that there was no difference with EPOST treatments in comparison to PRE treatments at 4 and 8 weeks WAT (Table 3). The PRE fb LPOST treatments provided 6% greater control of green pigweed in comparison to the PRE herbicide applications alone (Table 3). Two-pass treatments (PRE fb LPOST) provided up to 9% greater control of green pigweed than the EPOST treatment alone (Table 3).

S-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE reduced green pigweed density 83, 96, and 100%, respectively (Table 3). Imazethapyr + bentazon applied EPOST reduced green pigweed density 89% (Table 3). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced green pigweed density 98, 99, and 100%, respectively (Table 3). Orthogonal contrasts indicated that there was no significant difference in green pigweed density between PRE vs EPOST treatments, but two-pass weed management programs reduced green pigweed density 89% and 92% compared to PRE and EPOST treatments, respectively (Table 3).

S-metolachlor/metribuzin applied PRE did not reduce green pigweed biomass, but pyroxasulfone/sulfentrazone and flumioxazin/metribuzin/imazethapyr applied PRE reduced green pigweed biomass 92 and 100%, respectively (Table 3). Imazethapyr + bentazon applied EPOST reduced green pigweed biomass 87% (Table 3). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced green pigweed biomass 98, 99, and 100%, respectively (Table 3). Orthogonal contrasts indicated that there was no significant difference in green pigweed biomass between PRE vs EPOST treatments but two-pass treatments reduced biomass 91 and 92% compared to PRE and EPOST treatments, respectively (Table 3).

In other research, the sequential application of PRE herbicides such as imazethapyr, *S*-metolachlor + metribuzin, and flumetsulam/*S*-metolachlor followed by an application of glyphosate LPOST provided 99-100% control of pigweed in GR soybean (Stewart et al., 2011). In another study, the sequential application of glyphosate + chlorimuron or glyphosate + pyroxasulfone/flumioxazin applied PRE fb an application of glyphosate LPOST controlled pigweed 99-100% which was similar to the sequential application of glyphosate (Soltani et al., 2014).

3.4 Common Ragweed

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled common ragweed 21, 18, and 93%, respectively (Table 4).

Table 4. Percent control, density and dry biomass for AMBEL treated with a PRE, EPOST or 2-pass herbicide programs at Exeter, Ontario in 2021 (n = 1) and Ridgetown, Ontario in 2021 and 2022 (n = 5) [a]

Herbicide treatment	Rate	Timing	AMBEL control			AMBEL density	AMBEL dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		------------------ % ----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0 a	0.0 a
Non-treated control			0 c	0 d	0 d	47 g	69.9 d
S-metolachlor/metribuzin	1943	PRE	21 b	13 c	7 c	17 ef	47.9 d
Pyroxasulfone/sulfentrazone	300	PRE	18 b	14 c	8 c	34 fg	97.9 d
Flumi/metribuzin/imazethapyr	630	PRE	93 a	88 ab	82 b	3 abc	10.7 bc
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	83 b	78 b	14 de	6.4 c
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	95 ab	94 ab	4 abc	1.4 abc
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	93 ab	88 ab	10 cd	4.6 bc
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	100 a	99 a	1 ab	1.1 ab
Contrasts							
PRE vs EPOST			-	37 vs 83**	29 vs 78**	18 vs 14	52.1 vs 6.4**
PRE vs 2-pass			-	37 vs 97**	29 vs 95**	18 vs 5**	52.1 vs 2.4**
EPOST vs 2-pass			-	83 vs 97*	78 vs 95*	14 vs 5**	6.4 vs 2.4*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at $P < 0.05$.

* and ** denote significance at $P < 0.05$ and $P < 0.001$, respectively.

[a] Abbreviations: AMBEL, common ragweed; Bent, bentazon; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and 8 WAT, *S*-metolachlor/metribuzin and pyroxasulfone/sulfentrazone applied PRE provided only 7-14% control of common ragweed but flumioxazin/metribuzin/imazethapyr applied PRE provided 82-88% control of common ragweed (Table 4). Imazethapyr + bentazon applied EPOST provided 78-83% control of common ragweed. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST provided up to 95, 93, and 100% control of common ragweed, respectively (Table 4). Orthogonal contrasts indicated the EPOST treatments provided 46 and 49% greater control of common ragweed at 4 and 8 WAT, respectively (Table 4). The PRE fb LPOST controlled common ragweed 60 and 66% greater than the PRE treatments at 4 and 8 WAT, respectively. The PRE fb LPOST controlled common ragweed 14 and 17% greater than EPOST at 4 and 8 WAT, respectively (Table 4).

Pyroxasulfone/sulfentrazone applied PRE did not reduce common ragweed density (Table 4). .*S*-metolachlor/metribuzin and flumioxazin/metribuzin/imazethapyr applied PRE reduced common ragweed density 64 and 94%, respectively (Table 4). Imazethapyr + bentazon applied EPOST reduced common ragweed density 70% (Table 4). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop applied LPOST reduced common ragweed density 91, 79, and 98%, respectively (Table 4). Orthogonal contrasts indicated that there was no significant difference in common ragweed density between PRE vs EPOST treatments, but two-pass weed management programs reduced common ragweed density 72% greater than PRE treatments and 64% greater than the EPOST treatment (Table 4).

S-metolachlor/metribuzin and pyroxasulfone/sulfentrazone applied PRE did not affect common ragweed biomass, but flumioxazin/metribuzin/imazethapyr applied PRE reduced common ragweed biomass 85% (Table 4). Imazethapyr + bentazon applied EPOST reduced common ragweed biomass 91% (Table 4). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced common ragweed biomass 98, 93, and 98%, respectively (Table 4). Orthogonal contrasts indicated that common ragweed biomass was reduced 88% more with EPOST compared to PRE treatments and the two-pass programs reduced common ragweed biomass 95% more than the

PRE treatments. Two-pass treatments also reduced common ragweed biomass 63% compared to the EPOST treatment alone, respectively (Table 4).

Results are similar to other studies that have reported that the sequential application of PRE herbicides such as imazethapyr, *S*-metolachlor + metribuzin, and flumetsulam/*S*-metolachlor followed by an application of glyphosate LPOST provided 91-94% control of common ragweed in GR soybean (Stewart et al., 2011). In another study, the sequential application of a PRE herbicide followed by an application of glyphosate LPOST controlled common ragweed 96-98% which was comparable to the sequential application of glyphosate (Soltani et al., 2014).

3.5 Common Lambsquarters

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled common lambsquarters 24, 67, and 99%, respectively (Table 5).

Table 5. Percent control, density and dry biomass for CHEAL treated with a PRE, EPOST or 2-pass herbicide programs at Exeter, Ontario in 2021 (n = 1) and Ridgetown, Ontario in 2021 and 2022 (n = 4) [a]

Herbicide treatment	Rate	Timing	CHEAL control			CHEAL density	CHEAL dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		----------------- % -----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0.0 a	0.0 a
Non-treated control			0 c	0 d	0 c	75.2 e	18.7 c
S-metolachlor/metribuzin	1943	PRE	24 b	35 c	25 b	9.7 d	16.3 c
Pyroxasulfone/sulfentrazone	300	PRE	67 ab	66 bc	68 ab	1.3 bc	1.6 b
Flumi/metribuzin/imazethapyr	630	PRE	99 a	99 ab	98 a	0.7 abc	0.2 ab
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	95 ab	95 a	7.5 cd	0.9 b
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	97 ab	96 a	1.3 bc	0.7 ab
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	98 ab	98 a	1.1 abc	0.5 ab
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	100 a	100 a	0.3 ab	0.1 ab
Contrasts							
PRE vs EPOST			-	72 vs 95*	69 vs 95*	3.9 vs 7.5	6.0 vs 0.9
PRE vs 2-pass			-	72 vs 98**	69 vs 98**	3.9 vs 0.9*	6.0 vs 0.4**
EPOST vs 2-pass			-	95 vs 98	95 vs 98	7.5 vs 0.9*	0.9 vs 0.4

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

[a] Abbreviations: Bent, bentazon; CHEAL, common lambsquarters; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and 8 WAT, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled common lambsquarters 25-35, 66-68, and 98-99%, respectively (Table 5). Imazethapyr + bentazon applied EPOST provided 95% control of common lambsquarters. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST provided 96-97, 98, and 100% control of common lambsquarters, respectively (Table 5). Orthogonal contrasts indicated that there was 23 and 26% greater control of common lambsquarters with EPOST treatment in comparison to PRE treatments at 4 and 8 WAT (Table 5). The PRE fb LPOST treatments provided 26 and 29% greater control of common lambsquarters in comparison to the PRE herbicide applications alone at 4 and 8 WAT, respectively (Table 5). Two-pass treatments (PRE fb LPOST) did not provide any significant increase in control of common lambsquarters compared to the EPOST treatment alone (Table 5).

S-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE reduced common lambsquarters density 87, 98, and 99%, respectively (Table 5). Imazethapyr + bentazon applied

EPOST reduced common lambsquarters density 90% (Table 5). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced common lambsquarters density 98, 99, and 100%, respectively (Table 5). Orthogonal contrasts indicated that there was no significant difference in common lambsquarters density between PRE vs EPOST treatment, but two-pass weed management programs reduced common lambsquarters density 77% greater than PRE treatments and 88% greater than the EPOST treatment (Table 5).

S-metolachlor/metribuzin applied PRE did not reduce common lambsquarters biomass but pyroxasulfone/sulfentrazone and flumioxazin/metribuzin/imazethapyr applied PRE reduced common lambsquarters biomass 91 and 99%, respectively (Table 5). Imazethapyr + bentazon applied EPOST reduced common lambsquarters biomass 95% (Table 5). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced common lambsquarters biomass 96, 97, and 99%, respectively (Table 5). Orthogonal contrasts indicated that there was no significant difference in common lambsquarters biomass between PRE vs EPOST or EPOST vs two-pass treatments, but the two-pass treatments reduced biomass 93% greater than the PRE treatments (Table 5).

Results are similar to Stewart et al. (2014) that showed 97-98% control of common lambsquarters with the sequential application of PRE herbicides such as imazethapyr, S-metolachlor + metribuzin and flumetsulam/*S*-metolachlor followed by an application of glyphosate in GR soybean. Similarly, Soltani et al. (2014) observed that the sequential application of a PRE herbicide followed by an application of glyphosate LPOST provided 99-100% control of common lambsquarters in GR soybean. Gonzini et al. (1999) also reported a 13-27% increase in control of common lambsquarters when PRE herbicides such as chlorimuron + metribuzin, cloransulam-methyl, or sulfentrazone were followed by glyphosate (LPOST).

3.6 Barnyardgrass

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled barnyardgrass 93, 78, and 91%, respectively (Table 6).

Table 6. Percent control, density and dry biomass for ECHCG treated with a PRE, EPOST or 2-pass herbicide programs at Ridgetown, Ontario in 2022 (n = 3) [a]

Herbicide treatment	Rate	Timing	ECHCG control			ECHCG density	ECHCG dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		---------------- % ----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0 a	0.0 a
Non-treated control			0 b	0 d	0 c	29 c	25.8 c
S-metolachlor/metribuzin	1943	PRE	93 a	93 ab	91 ab	10 b	3.3 b
Pyroxasulfone/sulfentrazone	300	PRE	78 a	77 c	77 b	12 bc	4.4 b
Flumi/metribuzin/imazethapyr	630	PRE	91 a	90 b	89 ab	8 b	3.5 b
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	76 c	76 b	6 b	1.3 ab
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	97 ab	97 a	4 b	0.5 ab
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	95 ab	95 a	4 b	1.0 ab
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	98 a	97 a	3 b	0.6 ab
Contrasts							
PRE vs EPOST			-	87 vs 76*	87 vs 76*	10 vs 6	3.7 vs 1.3*
PRE vs 2-pass			-	87 vs 97**	87 vs 96**	10 vs 4*	3.7 vs 0.7*
EPOST vs 2-pass			-	76 vs 97**	76 vs 96**	6 vs 4	1.3 vs 0.7

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

[a] Abbreviations: Bent, bentazon; ECHCG, barnyardgrass; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and 8 WAT, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE provided 91-93, 77, and 89-90% control of barnyardgrass, respectively (Table 6). Imazethapyr + bentazon applied EPOST provided 76% control of barnyardgrass. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST provided 97, 95, and 97-98% control of barnyardgrass, respectively (Table 6). Orthogonal contrasts indicate that the PRE treatments provided 11% greater barnyardgrass control than the EPOST treatment at 4 and 8 WAT (Table 6). The PRE fb LPOST treatments provided 10 and 9% greater control of barnyardgrass in comparison to the PRE treatments alone at 4 and 8 WAT, respectively. The PRE fb LPOST treatments provided 21 and 20% greater control of barnyardgrass in comparison to the EPOST treatment at 4 and 8 WAT, respectively (Table 6).

Pyroxasulfone/sulfentrazone applied PRE did not reduce barnyardgrass density, but *S*-metolachlor/metribuzin and flumioxazin/metribuzin/imazethapyr applied PRE reduced barnyardgrass density 66 and 72%, respectively (Table 6). Imazethapyr + bentazon applied EPOST reduced barnyardgrass density 79% (Table 4). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced barnyardgrass density 86, 86, and 90%, respectively (Table 6). Orthogonal contrasts indicated that there was no significant difference in barnyardgrass density between PRE vs EPOST or EPOST vs two-pass treatments, but the two-pass weed management programs reduced barnyardgrass density 60% greater than PRE alone treatments (Table 6).

S-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE reduced barnyardgrass biomass 87, 83, and 86%, respectively (Table 6). Imazethapyr + bentazon applied EPOST reduced barnyardgrass biomass 95% (Table 6). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced barnyardgrass biomass 98, 96, and 98%, respectively (Table 6). Orthogonal contrasts indicated that barnyardgrass biomass was reduced 65% greater with EPOST compared to PRE treatments and 81% with two-pass treatments compared to the PRE treatments. The two-pass treatments reduced barnyardgrass biomass similar to the EPOST treatment (Table 6).

Results are similar to other studies in which the sequential application of a PRE herbicide followed by an application of glyphosate LPOST controlled barnyardgrass 97-100% in GR soybean, which was the same as the sequential application of glyphosate (EPOST fb LPOST) (Soltani et al., 2014).

3.7 Green Foxtail

At 2 WAE, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE controlled green foxtail 55, 72, and 95%, respectively (Table 7).

Table 7. Percent control, density and dry biomass for SETVI treated with a PRE, EPOST or 2-pass herbicide programs at Exeter, Ontario in 2021 (n = 1) and Ridgetown, Ontario in 2021 and 2022 (n = 5) [a]

Herbicide treatment	Rate	Timing	SETVI control			SETVI density	SETVI dry biomass
			2 WAE	4 WAT	8 WAT		
	g ai ha^{-1}		----------------- % -----------------			plants m^{-2}	g m^{-2}
Weed-free control			100	100	100	0 a	0.0 a
Non-treated control			0 c	0 d	0 e	138 d	62.6 e
S-metolachlor/metribuzin	1943	PRE	55 a	62 c	62 d	33 c	13.4 d
Pyroxasulfone/sulfentrazone	300	PRE	72 a	71 bc	68 cd	40 c	20.3 d
Flumi/metribuzin/imazethapyr	630	PRE	95 a	95 ab	93 abc	16 b	2.4 bc
Imazethapyr + bentazon + UAN	75 + 840 + 2 L ha^{-1}	EPOST	-	82 abc	79 bcd	47 c	5.1 cd
S-metolachlor/metribuzin + bent + fom + quiz + SM	1943 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	98 a	97 ab	7 b	1.1 abc
Pyroxasulfone/sulfentrazone + bent + fom + quiz + SM	300 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	97 a	96 ab	8 b	1.5 abc
Flumi/metribuzin/imazethapyr + bent + fom + quiz + SM	630 + 840 + 240 + 48 + 0.5% v/v	PRE + LPOST	-	99 a	99 a	4 b	0.2 ab
Contrasts							
PRE vs EPOST			-	78 vs 82	76 vs 79	29 vs 47*	12.0 vs 5.1
PRE vs 2-pass			-	78 vs 98**	76 vs 98**	29 vs 7**	12.0 vs 0.9**
EPOST vs 2-pass			-	82 vs 98*	79 vs 98*	47 vs 7**	5.1 vs 0.9**

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at $P < 0.05$.

* and ** denote significance at $P < 0.05$ and $P < 0.001$, respectively.

[a] Abbreviations: Bent, bentazon; Flumi, flumioxazin; Fom, fomesafen; EPOST, postemergence up to 2.5 cm weeds; LPOST, postemergence up to 5 cm weed escapes and prior to V5 soybean; PRE, preemergence; Quiz, quizalofop-p-ethyl; SETVI, green foxtail; SM, Sure-Mix; UAN, urea ammonium nitrate; WAE, weeks after crop emergence; WAT, weeks after LPOST herbicide application.

At 4 and 8 WAT, *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE provided 62, 68-71, and 93-95% control of green foxtail, respectively (Table 7). Imazethapyr + bentazon applied EPOST provided 79-82% control of green foxtail. *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST provided up to 98, 97, and 99% control of green foxtail, respectively (Table 7). Orthogonal contrasts was no difference between PRE treatments and EPOST at 4 and 8 WAT (Table 7). The PRE fb LPOST treatments provided 20 and 22% greater control of green foxtail in comparison to the PRE treatments, at 4 and 8 WAT, respectively The PRE fb LPOST treatments provided 16 and 19% greater control of green foxtail in comparison to the EPOST treatments, at 4 and 8 WAT, respectively (Table 7).

S-metolachlor/metribuzin, pyroxasulfone/sulfentrazone and flumioxazin/metribuzin/imazethapyr applied PRE reduced green foxtail density 76, 71, and 88%, respectively (Table 7). Imazethapyr + bentazon applied EPOST reduced green foxtail density 66% (Table 4). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced green foxtail density 95, 94, and 97%, respectively (Table 7). Orthogonal contrasts indicated that PRE treatments reduced green foxtail density 38% greater than EPOST treatments alone, two-pass treatments reduced green foxtail density 76% greater than PRE treatments, and two-pass treatments reduced green foxtail density 85% more than EPOST (Table 7).

S-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE reduced green foxtail biomass 79, 68, and 96%, respectively (Table 7). Imazethapyr + bentazon applied EPOST reduced green foxtail biomass 92% (Table 7). *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST reduced green foxtail biomass 98, 98, and 100%, respectively (Table 7). Orthogonal contrasts indicated that there was no difference between PRE vs EPOST treatments on green foxtail biomass. The two-pass treatments reduced green foxtail biomass 93% more than the PRE treatments and the two-pass program reduced green biomass 82% more than the EPOST (Table 7).

Results are similar to Stewart et al. (2014) findings that showed 99-100% control of green foxtail with the sequential application of PRE herbicides such as imazethapyr, *S*-metolachlor + metribuzin and flumetsulam/*S*-metolachlor followed by an application of glyphosate in GR soybean. Similarly, Soltani et al. (2014) observed that the sequential application of a PRE herbicide followed by an application of glyphosate LPOST provided 99-100% control of green foxtail in GR soybean. Gonzini et al. (1999) reported that giant foxtail control was increased by 2-15% when PRE herbicides such as chlorimuron + metribuzin, cloransulam-methyl, or sulfentrazone were applied sequentially with glyphosate LPOST.

4. Conclusions

Weed control with the herbicide programs evaluated was weed species-specific. Velvetleaf was controlled the best with flumioxazin/metribuzin/imazethapyr applied PRE, imazethapyr + bentazon applied EPOST, and pyroxasulfone/sulfentrazone or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST.

Green pigweed was best controlled with pyroxasulfone/sulfentrazone and flumioxazin/metribuzin/imazethapyr applied PRE, imazethapyr + bentazon applied EPOST, and *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST.

Common ragweed was best controlled with *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST.

Common lambsquarters was best controlled with flumioxazin/metribuzin/imazethapyr applied PRE, imazethapyr + bentazon applied EPOST, and *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST.

Barnyardgrass was best controlled with *S*-metolachlor/metribuzin and flumioxazin/metribuzin/imazethapyr applied PRE, and *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST.

Green foxtail was best controlled with flumioxazin/metribuzin/imazethapyr applied PRE, and *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST.

All PRE or EPOST herbicide treatments applied alone caused minimal and transient injury in soybean, but *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, or flumioxazin/metribuzin/imazethapyr applied PRE fb bentazon + fomesafen + quizalofop LPOST caused 20-22% injury in soybean.

Weed interference reduced soybean yield 40%. Among various treatments evaluated, weed interference with *S*-metolachlor/metribuzin and pyroxasulfone/sulfentrazone applied PRE reduced soybean yield 25 and 31%, respectively, but all other PRE, EPOST or PRE fb LPOST treatments evaluated resulted in soybean yield that was similar to the weed-free control.

This study concludes that the two-pass programs of *S*-metolachlor/metribuzin, pyroxasulfone/sulfentrazone, and flumioxazin/metribuzin/imazethapyr applied PRE followed by bentazon + fomesafen + quizalofop applied LPOST provides broad spectrum control of common annual broadleaf and grass weeds in Ontario. Two-pass herbicide programs combine herbicides with different modes of action and have the potential to reduce the selection pressure for the evolution of herbicide-resistant weeds in Ontario.

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Authors Contributions

Drs. Peter Sikkema and Nader Soltani were responsible for the study design and writing of this manuscript. Christy Shropshire conducted the statistical analysis of the data collected.

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Exploring Crop Choices: Benefits, Challenges, and Rationale Among Rwandan Farmers

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Abstract

Farming decisions on crop choices are guided by different factors including natural conditions, household needs, traditions, stakeholder recommendations, and productivity. The best decision varies for each farmer based on specific circumstances. There are both benefits and challenges in farmers' crop growing experience. In Rwanda, agriculture employs 70% of the population, contributing 33% to the GDP across three main agricultural seasons. However, food and nutritional insecurity remain pressing issue affecting both human and economic progress. This study explored the rationale, benefits, and challenges of farmers' choices. This study used a qualitative descriptive approach, conducting six focus group discussions (FGDs) in each participating district. Each FGD comprised 10 participants, ensuring gender balance. Recruitment was facilitated by local community health workers (CHWs), with participants providing informed consent. Trained data collectors utilized voice recorders to collect the data. The researchers transcribed the data verbatim, anonymized the data, and translated the same data into English. Data analysis revealed four key themes: reasons for cultivation, factors influencing crop choice, farmers' livelihoods, and farming challenges. Findings highlight the need for holistic and context-specific solutions in Rwandan agricultural development, emphasizing stakeholder collaboration to support informed decision-making and sustainable agriculture.

Keywords: benefits, challenges, crops, exploration, farmers, Rwanda

1. Introduction

The Sustainable Development Goals (SDGs) encompass critical global issues, including eliminating poverty and hunger, health enhancement, climate action, and ecosystem preservation. Despite global efforts, challenges persist with approximately one in ten people worldwide still experience hunger, while one in three people experience food insecurity due to insufficient and unreliable access to food (ten Berge et al., 2019). Poverty plays a crucial role in driving hunger and malnutrition, leading to inadequate food access and malnutrition (Katona & Katona-Apte, 2008), which in turn, results in severe health repercussions and diminished productivity. Notably, malnutrition affects 149 million children globally, leading to stunting and wasting (Maniragaba et al., 2023). Extreme weather events exacerbate food insecurity, amplifying the urgency for SDGs driven solutions. Although the World Health Organization (WHO) committed to nine global health targets, including eradicating all forms of malnutrition by 2030 (Hasan et al., 2022), hunger affected approximately 783 million people in 2022, with significant proportions in sub-Saharan region (FAO et al., 2022). Population growth in this region exacerbates food demand, putting pressure on agricultural resources and hindering the adoption of sustainable farming practices (Van Ittersum et al., 2016).

Rwanda, aiming for economic transformation, relies heavily on agriculture, yet faces challenges due to limited, reliance on rainfed agriculture, and postharvest losses (Musabyemariya et al., 2018) (NISR, 2021b). Soil erosion, deforestation, and land degradation, further threaten productivity (Karamage et al., 2016). Government led initiatives like crop intensification programs seek to enhance productivity, but challenges persist including monocropping and harvest losses (MINAGRI, 2018).

Previous studies have highlighted the influence of factors on crop choices among Rwandan farmers including agroecological zones, market demand, profitability, government policies and local knowledge (Mugenzi et al., 2011; Nahayo et al., 2017). Additionally studies have examined the significance of specific crops within the Rwandan agricultural sector (Isaacs et al., 2016). The importance of climate resilience and adaptation in crop choices has gained attention given the impacts of climate change on agriculture (Clay & King, 2019). Programs including crop intensification program (CIP) have provided guidance and support to farmers in selecting suitable crops aligned with national agricultural strategies (MINAGRI, 2013; Nahayo et al., 2017). Further research should focus on a comprehensive exploration of crop choices among Rwandan farmers, delving into their benefits, challenges, and rationale. Understanding the specific decision-making processes, preferences, and relative importance of various factors in crop choice decisions is essential. Additionally, there is a need for economic analysis to compare different crop options in terms of profitability and income generation. Evaluating the long-term impacts of government policies and programs, on farmers' crop choices and agricultural practices is also imperative. Within this context, this study investigates farmers 'crop cultivation experiences, focusing on the factors influencing crop choices, livelihood impacts, and agricultural challenges. By understanding these dynamics, the study aims to contribute insights into successful agricultural practices that address malnutrition and promote income growth, aligning with Rwanda's economic transformation objectives.

2. Study Methods

2.1 Study Design

A qualitative exploratory descriptive design was used for this study. The data were collected utilizing a focus group discussion (FGD) approach. This approach allowed for a thorough exploration of the factors influencing farmers' choices and their potential impact on livelihood.

2.2 Study Setting

The study was conducted in regions known for their significant agricultural potential in the western part of Rwanda, specifically within the districts of Nyamagabe, Karongi, and Nyabihu. These districts are also characterized by a notably higher incidence of undernutrition among children aged less than 5 years (NISR, 2021a). Having three different settings enhanced the comprehensiveness, reliability and applicability of findings hence this contributes to a more robust understanding of agricultural decision-making processes.

2.3 Study Population, Participant Selection, and Inclusion Criteria

All parents engaged in agriculture within the selected districts were eligible to participate in the study. However, a purposive sampling method was utilized to recruit 60 participants, 20 from each district, and half of which was either sex. The participants might be engaging in one of the suggested farming practices, including tea, Irish potato, or subsistence farming, and having an under five-year-old child at home. All the participants were aged above 21 years and able to communicate in Kinyarwanda (native language).

2.4 Data Collection and Instrument

A structured interview guide was formulated in alignment with the study objectives and existing literature to facilitate Focus Group Discussions (FGDs) (Plummer, 2017). The guide consisted of ten main topics applicable to all sessions and was tested before the research was implemented by conducting two FGDs of 4 people each in a different area than the study area. After this pilot session, the participants also commented on how they understood the guide questions. This has helped to refine the tool. Local community health workers (CHWs) in each district helped mobilize FGD participants. Sessions occurred in quiet rooms within local government administrative buildings. More probing options were provided to identify farmers' experience in growing crops of their choices. Therefore, the interview of this study was structured in main three sections including factors of choices, impacts of chosen crops and challenges experienced while implementing their choices. An in-depth face to face FGD method was opted for to enable farmers freely express their views.

The participants were told that a board with "Do not disturb" was hanging outside the room where the interview was being conducted. Participants were provided with information about the study's importance, objectives, and procedures during the debriefing sessions. Before starting the FGD, participants were invited to sign individual consent forms, and each participant was given a unique code number.

Each group consisted of 10 mothers or fathers, with two sessions held in each district. The duration of each FGD varied from 60 to 90 minutes, two trained research assistants conducted the data collection—one moderated the discussion, and the other took manual notes to supplement the voice recordings. The FGDs were conducted in Kinyarwanda, the participant's native language. The data collection procedure was consistent across the three settings.

2.5 Data Analysis

The audio recordings were transferred to the principal investigator's laptop, transcribed and translated by research assistants from the local language to English. The investigator did the analysis using qualitative content analysis (Lacey & Luff, 2009). To mask the identification of participants, each statement received an indication code indicating the district, FGD gender composition, and serial number of the participant, facilitating differentiation and organization of data (*e.g.*, KGF2 represents a focus group discussion (FGD) conducted with female participants from district KG, with participant number 2). The four levels of coding were utilized to code the data in the following way:

Coding at Step One: The research investigators read the whole data line by line of each bunch of data. They then assigned codes to the content in the FGD sessions.

Coding at Step Two: The investigators reviewed and compared the coded data and then these were clustered by creating larger categories compared to those from step one coding.

Coding at Step Three: The investigators transformed the categories of codes into central themes that represent larger patterns and relationships between bunches of data having commonalities.

2.6 Ethical Considerations

The study obtained ethical approval from the University of Rwanda Institutional Review Board and approval from the National Institute of Statistics. Authorization to collect field data was granted by the Ministry of Local Governance. Participants were informed about the study's design, objectives, and importance and provided individual informed consent. To maintain anonymity, participants were assigned codes or pseudonyms. Participants were guaranteed confidentiality and anonymity, with assurance that their information would not be shared or linked to them. They were also informed of their rights including to withdraw from the study at any time.

2.7 Trustworthiness

The study maintained qualitative research principles, including credibility, dependability, confirmability, and transferability (Lacey & Luff, 2009; Tobin & Begley, 2004). Credibility was ensured by employing consistent questions, achieving data saturation in all interviews, and confirming the accuracy of the transcribed data with participants. Dependability was enhanced by describing the methodology and organizing the data into themes and Transferability was ensured by offering a detailed description of the study settings and context, facilitating replication by future researchers conducting similar studies.

3. Results

3.1 Demographics

Sixty farmers from three districts participated in six FGDs, with each district hosting two sessions—one for males and one for females. The female participants ranged in age from 24 to 59 years, while the male participants' ages varied from 27 to 68 years. Participants were predominantly cultivated tea as export crop, food crops (subsistence farming), and Irish potatoes.

3.2 Emerged Themes

Table 1. The themes identified from the analysis of FGDs

Research questions	Themes	Categories	Description or examples
What are the driving factors that influence farmers' choices of crops,	1. Reasons for cultivation	i. Income &Profit	Farmers prefer crops that can help them to make earnings and gains obtained from doing agriculture and selling farming products.
		ii. Export	This means a monthly regular income generated from growing export crops.
		iii. Household consumption	All types of crops are grown to provide food consumed at the household level.
	2. Factors influencing the choice of crops	i. Soil Climate	Environmental factors that significantly influence crop production, and agricultural practices.
		ii. Inheritance	Passing down of agricultural knowledge, practices, and assets from one generation to the next within farming families.
		iii. Stakeholders 'recommendations	Farmers choose crops upon considering the advice or guidance provided by entities having a vested interest in the sector of agriculture.
How do these choices impact their livelihoods	3. Livelihood of Farmers	i. Family Nutrition	They choose crops that help the household to ensure all members of the family, children, women, and adults, receive the essential nutrients they need to maintain good health and wellbeing.
		ii. Financial support	They choose crops that when sold can provide monetary assistance to help farmers meet their financial needs or specific financial goals.
		iii. Self-financing	Farmers prefer crops that help to generate their own income or financial resources to support and sustain their agricultural operations without relying heavily on external sources.
What challenges do farmers face in agriculture	4. Challenges in choice of farming	i. Pests and diseases	This is the category of challenges that can lead to reduced crop yields, lower-quality produce, and increased production costs.
		ii. Accessing agricultural inputs	Accessing agricultural inputs is the process of obtaining and acquiring various essential resources and materials including seeds, fertilizers, pesticides, equipment, technology, and other resources necessary for farming management.
		iii. Climate change	This means various impacts of changing climatic conditions such as alterations in temperature and precipitation on agricultural practices and crop production patterns.
		iv. Soil and crop incompatibility	When the soil's characteristics and conditions are not suitable for the successful growth and development of a crop. The consequences are poor crop performance, reduced yields, and susceptibility to pests, diseases, and environmental stressors.

3.1.1 First Theme: Reasons for Cultivation

Farmers have various crops, and none of farmers can grow one crop only; however, some of the crops grown are given more value than others. There are underlying motivations and factors that drive farmers to engage in agricultural activities. Understanding the reasons for cultivation helps gain insights into the goals, priorities, and challenges that shape agricultural practices. Three main categories underscore the reasons for cultivation.

(1) Income and Profit

Cash crops are typically cultivated in substantial quantities for sale, often in urban markets. These crops are predominantly monocultured, although occasional intercropping may occur, with the primary crop designation reserved for cash crops. The cultivation of cash crops is characterized by the utilization of modern agricultural techniques, such as the application of fertilizers and pesticides, aimed at enhancing both yield and quality. Participants identify them in the following manner.

NBF9: "*They are very productive; for example, when we grow Irish potatoes, we get enough harvest, and when we grow wheat, we can even sell some of the harvest. In addition, this is the same when we grow Irish potatoes.*"

NBM3: "*Briefly, by selling our produce, we can acquire other foods and necessities that we do not cultivate ourselves. For instance, if we cultivate wheat, we can sell a portion of it to purchase rice or maize flour. This allows us to diversify our children's dietary needs. Sometimes, we may consider additional nutritional requirements for our children and use the proceeds from our harvest to buy items such as dried or small fish, cooking oil, salt, and more.*"

NHF2: "*The harvest holds immense significance as it not only contributes to covering school fees and children's expenses but also enables the purchase of additional food items for the family.*"

NBM8: "*The harvest from Irish potatoes is sold; then we can rear any cattle from that harvest sold. The remaining harvest feeds the family, and the cattle bought will provide the manure to keep the soil fertile and productive.*"

(2) Export

Export crops play a pivotal role in generating revenue for countries, stimulating economic growth, and fostering job opportunities. These crops are frequently cultivated as monocultures in substantial quantities, employing modern agricultural techniques, and often receiving government support. These crops are typically not intended for direct consumption by farmers due to their non-food nature. Farmers describe them as follows:

NBM2: "*The primary motivation behind our tea cultivation is multifaceted. Initially, we were encouraged to grow tea through mobilization efforts, and over time, we've come to appreciate its numerous benefits. One of the most compelling reasons to cultivate tea is the reliable monthly income it provides. For those who rely on a steady income to support their livelihoods, the consistent monthly harvests from tea serve as a dependable source of financial stability. This income not only fulfills immediate family needs but also offers flexibility during emergencies, enabling access to funds or credit for urgent expenses or purchases. Moreover, tea farming facilitates easy enrollment in medical insurance schemes, ensuring the health and well-being of farmers and their families without fear of penalty. The combination of financial security, accessibility to credit, and healthcare benefits makes tea cultivation an attractive option for us, driving our deep involvement in tea plantation activities. Thank you for your attention. Thank you very much!*"

NBM14: "*Tea cultivation stands as a vital pillar in the livelihoods of the farmers you see here. Through our cooperative, we supply the harvest, and the income we receive at the end of the month enables us to purchase essential items for our homes.*"

(3) Household Consumption

Staple crops serve as dependable sources of sustenance, particularly for farmers and local populations. They are typically cultivated under subsistence farming practices, often at low cost. One of their key attributes is their ability to be stored for extended periods, making them essential for ensuring food security. This category encompasses a wide range of crops, encompassing both staple and non-staple varieties, highlighting its crucial role in the overall food supply system.

The NBF5 cultivar: "*Vegetables, including green vegetables and carrots, are among the foods that are very important for fighting against malnutrition among children.*"

According to the NBM5: "*The benefits of growing tamarillos; malnourished children are recommended to take fruits. For the benefit of growing green vegetables, malnourished children are recommended to consume green leafy vegetables. That is the benefit of growing vegetables.*"

In the NBF10 treatment: "*When we grow maize, we sell it after harvesting. Then, we take the money we go to the market and buy other things we need so that we can feed the children well. We also buy other food needs that we don't grow like vegetables, beans, Irish and sweet potatoes, dry fishes, or sometimes meat after selling the harvest from the grown maize so that we can prepare a proper diet.*"

KGF2: "*We primarily cultivate sweet potatoes and beans because they serve as our main food staples at home. We harvest these crops to sustain our family's food needs and also sell a portion of our harvest for additional income.*"

3.1.2 Second Theme: Factors Influencing the Choice of Crops

Participants articulated a multitude of rationales underpinning their crop selection. These diverse motives have influenced farmers' decisions to cultivate crops they believe best respond to the underlying reasons for the choice.

(1) Soil and Climate

When crops align with the prevailing environmental conditions, they thrive and flourish robustly. They also exhibit resilience in the face of environmental challenges. In such circumstances, farmers gain access to dependable sources of sustenance, thereby mitigating hunger and malnutrition and making significant strides toward achieving food security. Participants articulated this phenomenon as follows:

NHM2: "*In our cold climate, crops that thrive in similar conditions are preferred for cultivation. Conversely, crops suited to hot climates are not as suitable here. We select crops that align with the climate of our district for optimal productivity.*"

"*Here, in our region, the choice of crop seeds to grow depends on the specific soil characteristics of different areas. Since the inception of the TUBURA initiative, we have consistently cultivated maize, which has proven successful. Additionally, beans have been a productive crop, though occasional challenges due to climate change or unfavorable conditions have been encountered. Our selection of crops is based on their compatibility with our soil type.*"

KGF2: "*Of course, Our soil is ideal for growing sweet potatoes, ensuring families can feed their children.*"

(2) Inheritance

Participants highlighted the inheritance of choosing crops as a way through which they become aware of the growing crops that their ancestors have been growing. Farmers are more likely to grow crops that they are familiar with and that they know how to grow successfully. Participants expressed inheritance in the following statements:

NBF3: "*You can see our region is for growing Irish potatoes. A child from a family that grows Irish potatoes will grow the same crop of Irish potatoes when he becomes mature as he sees his parents growing the same.*"

KGM1: "*All these crops are grown here. As far as I know, we have inherited the crops that our elders (parents and relatives) used to grow. Additionally, TUBURA has trained us in the use of agricultural inputs. For example, if you used to grow maize in a certain way, now we can cultivate it using various types of fertilizers during both planting and weeding.*"

NBM9: "*I see that many people get land from their parents, although you can buy more if you have money, land, a variety of crops, and sometimes the way you manage soil comes from your elders. Like myself, most of the varieties of crops I have were also grown by my parents.*"

(3) Stakeholders' Recommendations

The agricultural sector is a wide field where various stakeholders intervene for multiple purposes. Stakeholders can include farmers, consumers, traders, processors, retailers, government, and nongovernmental organizations (NGOs). They influence farmers in various ways, including by providing information related to markets of either inputs or harvests. They can offer financial incentives to grow certain crops and can even provide technical assistance to help farmers grow crops more efficiently. The next statements show the major areas of collaboration with stakeholders like TUBURA (Prosper-a company helping in accessing better inputs), and Ejo Heza (Brighter Tomorrow-a saving scheme encouraging people to save for their future).

KGF4: "*Prior to the TUBURA intervention, we cultivated an unproductive variety of maize. Following TUBURA's assistance, we received an improved and highly productive variety of maize surpassing the yield of our previous crop. Moreover, the availability of other agricultural inputs, including fertilizers, payable in instalments has proven invaluable.*"

NBF7: "*We harvest avocados when they are ripe and sell them to the partners facilitated by TUBURA. These partners conduct field visits to assess the quality of the avocados before purchasing them at fair prices. As for maize, we primarily use the harvest to feed our families, while the surplus is processed into maize flour. Thanks to this, we no longer need to purchase maize flour.*"

According to the NBF10: "*Among the additional advantages of cultivating tea, rural residents like us who couldn't participate in the EJO HEZA initiative previously may have faced constraints due to limited financial resources. However, our engagement in the EJO HEZA savings initiative has been made possible through tea cultivation. Furthermore, the program offers incentives and awards, particularly at the end of each year, based on the quantity of tea supplied.*"

3.1.3 Third Theme: Livelihood of Farmers

Farmers are often referred to as the backbone of food systems and are primarily responsible for cultivating crops to sustain local communities. The selection of cultivated crops is highly important for farmers because cultivation directly affects their livelihoods. In addition to meeting the dietary needs of their communities, selling a portion of their harvest contributes to increased income and overall improvement in quality of life. These profits can further be channeled into investments, encompassing both in farming endeavors and nonfarm activities, fostering sustainable growth and prosperity.

(1) Family Nutrition

Household food security refers to having sufficient and nutritious food to maintain an active and healthy life. Subsistence farmers typically produce most of the food they need for their households, while larger farming investors prefer to obtain much of the household food needs from food markets. This is especially true when monoculture becomes the dominant agricultural practice.

KGF4: "*The harvest of these sweet potatoes is only for feeding the family, but I sell some portions sometimes depending on the occasion; on some occasions, they are very productive, and sometimes less productive depending on the season.*"

NBM6: "*Let's discuss our tea production: We sell our harvest and use the proceeds to address various family needs. As for maize and beans, we cultivate them primarily for household consumption, selling any surplus to supplement our income.*"

NBM3: "*Our cultivated crops play a vital role in maintaining a balanced diet. We also have our kitchen gardens where we grow nutritious vegetables these are important for their protective properties. The simplicity of managing these gardens allows for the cultivation of various vegetables like cabbage, carrots, and greens without requiring extensive space. These vegetables contribute significantly to having a balanced diet. While Irish and sweet potatoes, along with cassavas, provide essential energy, their productivity may vary. Nonetheless, they form part of our crop repertoire. We prioritize personal consumption before considering sales at the market. Additionally, we raise cattle for milk and chickens that can give eggs, they can as well give meat. Thank you for your attention.*"

(2) Financial Support

Farming is the primary source of income among farmers. Selling their harvest provides them with the money they need to buy clothing, shelter, and pay for education and health care. As living standards rise to meet sustainable development goals (SDGs), everyone will need to pay for health insurance, universal education, and other essential services. Farmers also report that farming helps them to pay for insurance, save money, and even purchase manure to boost crop production.

NBM7: "*We sell the harvest of Irish potatoes and the income serves to support various activities, including the access and support to cattle rearing. The surplus from the harvest provides food for the family. However, the other part of the income helps to get the fertilizer which maintains soil fertility and productivity. Additionally, the proceeds from the harvest assist in paying school fees for children and ensuring food security for the family.*"

NBF7: "*The advantage of cultivating tea lies in its transformative impact on our ability to participate in the EJO HEZA savings initiative. Previously hindered by limited financial capacity, our involvement is now feasible due to income generated from tea cultivation. Moreover, the management of tea companies offers incentives and rewards based on the quantity of tea supplied, enhancing motivation. Additionally, tea farming provides financial flexibility, enabling access to funds in emergencies without waiting the end of the month or facilitating purchases of food through credit. Furthermore, tea farmers can afford the payment of medica insurance without delay.*"

NHM4: "*Here, you can obtain a jerrycan of 20 liters of banana alcohol, which you can sell for six thousand [Rwandan francs]. Since neither you nor your child can consume it, you sell it to ensure your child's well-being. With the proceeds, you purchase porridge flour and other essential food items to maintain your child's health. After ensuring your child's needs are met, you may also indulge in a bottle yourself, knowing your child's welfare is secured.*"

(3) Self-Financing

The sustainability of farming relies on continued farming activities. Farmers use their usual work to finance this by obtaining seeds, fertilizers, and other agricultural inputs, including the cost of labor and transportation. It can also lead to facilitating access to new farming technologies.

NBF8: "*Regarding Irish potatoes: The harvest of Irish potatoes serves as the primary source of sustenance for our family. A portion is allocated for sale, contributing to savings through a community group savings scheme, while the remainder is preserved as seeds for the next planting season. This same practice is applied to maize and wheat; a portion is consumed by the family, another portion is sold, and the rest is retained for future planting. Selling is essential, as it also help to buy cattle that will also provide organic manure. Conversely, tea cultivation yields weekly harvests, directly supplied to processing factories. Thank you!*"

KGM2: "*The advantage lies in our practice of preserving seeds like beans. When they yield crops, as demonstrated here, the harvests can be substantial - ranging from one large bag to three bags, depending on the* *cultivated land's size. There are occasions when one hesitates to consume these seeds immediately, recognizing their potential for future yields. In such instances, instead of depleting the seed stock, individuals may opt to purchase food from shops while safeguarding the seeds for the upcoming agricultural season. Some may even sell produce like juices to acquire additional sustenance, all while ensuring the continuity of seed preservation for future cultivation.*"

The NBM4: "*The maize/corn harvest is very supportive; during the productive season, it provides enough harvest, and some portion of the harvest can be sold. This truly helps us to get inputs or buy some cattle that are also very supportive in our agricultural practices through providing organic manure.*"

3.1.4 Fourth theme: Challenges in the Choice of Farming

Agriculture is known as a challenging field. These challenges are becoming increasingly complex. Farmers are dealing with many obstacles, including climate change, pests and diseases, market volatility, population growth, and limited resources. Approximately 90% of participants raised concerns about the challenges encountered in agriculture.

(1) Pests and Diseases

Currently, pests and diseases constitute a major threat to food security. They can damage crops and reduce yields, which can make it difficult for people to reach the recommended aspects of food security. When pests and diseases spread through agricultural fields, it becomes difficult to ensure their control, which contributes to increased losses.

NHM5: "*Irish potatoes undergo drying when affected by diseases and pests. As they emerge above the soil or reach the surface, they exhibit a yellowish-brown discoloration, failing to develop properly. Eventually, they perish and display a coloration similar to healthy growth, though their condition remains compromised. Locally, this phenomenon is referred to as "sembeshi"(Late blight, probably).*"

NGM9: "*Furthermore, the maize stalk borer poses another challenge in maize cultivation. After planting maize, it is susceptible to attacks by these borers. Occasionally, we encounter delays in the provision of pesticides, both initially and subsequently, to combat these pests. Consequently, this presents another obstacle in maize farming. Similarly, we have faced challenges with cassava cultivation, where pests have affected the crops.*"

KGM3: "*We encountered challenges in cassava cultivation due to pest infestations.*"

(2) Accessing Agricultural Inputs

Resources that farmers use to produce crops are highly valuable for maximizing production and meeting food security requirements. The availability of sufficient quality and quantity is key to food production. These may include consumable inputs (seeds, fertilizers, pesticides, water) and capital inputs such as machinery and land. Participants have described their challenges in the following terms:

NBF9: "*Another challenge arises with the acquisition of fertilizers (inputs); if they arrive late and coincide with the approaching end of the season, planting maize may be delayed. Consequently, the critical period when maize requires rain for optimal growth might overlap with the imminent cessation of rainfall. During such instances, we experience reduced yields.*"

NBM10: "*Several challenges plague our agricultural practices, the most known among them being the soaring costs of agricultural inputs, particularly fertilizers. This exorbitant expense often results in insufficiency utilization of these inputs. Consequently, the increased cost may lead to the restricted or insufficient application of fertilizers, diminishing the cultivated land area as intended.*"

KGF6: "*Regarding inputs, especially fertilizers or seeds, when they are not expensive or late, they may not reach our area because it is very far, or sometimes the crops we grow are not included in those that benefit from the subsidy.*"

(3) Climate Change

Climate change denotes prolonged alterations in typical patterns impacting local or regional climates. It manifests through severe weather phenomena like droughts, floods, and heat waves, resulting in crop damage and diminished yields, thus hindering access to adequate food. Participants have encountered this experience, and now, they can reveal what climate change means in their farming experience.

The NBM11: "*In agriculture, we grapple with various challenges, including the impact of climate change. Heavy rainfall at times leads to diminished agricultural outputs, particularly affecting crops like beans and others.*

Conversely, there are instances of rainfall shortages during the agricultural season, further exacerbating our difficulties."

KGF5: "*We also contend with excessive sunshine and occasional disasters or hazards, such as landslides triggered by heavy rainfall.*"

The NHM6: "*drought may take a longer time, and in that period, there is no rain. The crops do not grow well, and there is no way of irrigating, as we are not able to buy the machine. Even the animals we rear fail to get water to drink.*"

(4) Soil and Crop Incompatibility

Soil and crop incompatibility refers to the inability of a crop to grow well on some soils. This can be caused by soil factors, including texture, drainage, acidity, and soil nutrient content. It affects people's food security in terms of crop yields, crop susceptibility to diseases and pests, and/or increased costs while trying to prevent and fight such challenges. The following are the testimonies of the participants.

KGM4: "*Moreover, our land suffers from excessive acidity, posing yet another challenge. Upon looking at it, it becomes evident that the soil acidity levels are not conducive for plant optimal growth.*"

NBM 6: "*The cultivation of our chosen crops presents challenges. Despite repeated attempts, achieving satisfactory yields proves elusive. This difficulty is exacerbated by the high costs of fertilizers and manure, coupled with the depletion of soil nutrients.*"

NBF9: "*Another challenge we encounter is related to bean cultivation. A perplexing issue arises when bean plants fail to produce beans upon reaching maturity; instead, they wither prematurely. This dilemma prompts us to question whether the issue lies with the soil quality or the effectiveness of fertilizers. It's plausible that either the soil composition or the quality of the seed beans used for cultivation may be contributing factors!*"

4. Discussion

This study explored the benefits, challenges, and rationale behind growing crops of choice among farmers in Rwanda. It utilized a descriptive qualitative approach and conducted focus group discussions (FGDs) to capture farmers' perspectives.

4.1 Reasons for Cultivation

Farmers cultivate a wide range of crops in their respective regions. The choice of crops is influenced by several factors, with key policies playing a significant role in shaping the transition from subsistence farming to market-oriented agriculture. Income pertains to the revenue derived from agricultural endeavors, encompassing the sale of crops, livestock, and associated goods. Many people around the globe rely on farming as the primary source of income, whether it is subsistence or large commercial agriculture. The farmers sell Irish potatoes and wheat, among others. Income helps individuals access other important foodstuffs required at home, as it also contributes to responding to other needs, including paying children's school fees and acquiring other farm resources, such as cattle. These findings align with those of the study by (Giller et al., 2021). Profit represents the surplus or financial gain obtained from agricultural operations after deducting all costs and expenses associated with production, such as labour, materials, equipment, land, and overhead expenses (Blank, 2018). This is an indicator of the financial viability and sustainability of an agricultural enterprise; it remains as important as reinvestment, expansion, and long-term success in the farming industry. The profit motive extends beyond the farm gate with opportunities to add value to agricultural products and capture additional income in the supply chain (Blank, 2018). Agriculture offers opportunities for diversified income streams, as many farmers engage in mixed farming, cultivating a variety of crops, which is also important for mitigating risks and generating income throughout the year (Blank, 2018). Moreover, agriculture is essential for economic development because it provides employment and income opportunities for rural communities (Hall et al., 2017).

Exporting as a reason for doing agriculture means that farmers prefer cultivating specific crops with the primary intent of selling them in international markets. This focus is driven by the desire to generate revenue and foreign exchange earnings, contribute to economic growth, and access a broader range of markets beyond domestic consumption. In our study area, large quantities of crops, such as tea, were grown in the Nyamagabe district, while coffee and pyrethrum were also found in substantial quantities in the Karongi and Nyabihu districts, respectively. These crops serve as sources of foreign exchange and could contribute to national economic growth. In addition to direct income from exporting the harvest, this type of agriculture is known to offer large amounts of seasonal employment directly and indirectly in rural areas (Hall et al., 2017). It also attracts foreign investment and allows for technology transfer as a joint venture between multinational corporations and local farmers (Remeikiene et al., 2018). Agriculture exports benefit from support from government policies, including incentives and subsidies; however, such support is associated with challenges such as price volatility, mostly due to international trade tensions.

With respect to household consumption, agriculture provides sustenance and livelihoods for countless communities. Its significant production portion is primarily geared toward household consumption, which is one of the fundamental reasons farmers engage in agriculture-(Giller et al., 2021). Farmers grow staple crops such as sweet potato and beans or high nutritional value crops such as vegetables or fruits. They can even sell staples such as maize to use the income for buying what is not grown at home. This self-reliance on homegrown produce ensures a consistent and affordable source of nourishment. In regions with unreliable access to markets, limited purchasing ability, or vulnerable food supply chains, household agriculture serves as a critical safety net against food shortages and crises (Giller et al., 2021). Agriculture ensures households access diverse, fresh, and nutritionally rich foods, promotes self-sufficiency, and empowers families to take control of their nutritional needs.

4.2 Factors Influencing the Choice of Crops.

Farmers may face a crucial decision on what crops to cultivate. The choices they make can have far-reaching consequences not only for their own livelihoods but also for the broader agricultural landscape. Exploring factors such as soil and climate inheritance and stakeholder recommendations are critical for both agricultural practices and the global food system.

Soil and climate are significant determinants guiding farmers in their choice of crops. The soil type directly affects nutrient availability, and each crop has unique soil requirements. Research findings reveal that maize, beans, and vegetables thrive in volcanic soils, whereas tea prospers at higher altitudes and in well-drained marshes. These findings align with those of studies by Nyirahabimana and Uwimana (2017) and soil classification research (Habarurema & Steiner, 1997; Rushemuka et al., 2014), which have facilitated regional categorization of crops based on Rwandan farming priorities. Soil also plays a role in crop susceptibility to erosion (Getnet & Mulu, 2021) and water retention, which are vital for normal crop growth (Easton & Bock, 2016).

Climate conditions are another crucial factor. Farmers select crops that can thrive in their region's weather. In Rwanda, for example, farmers opt for crops such as bananas and cassava, which are well suited to warm, humid climates (Moniruzzaman, 2015). Climate is pivotal in determining crop suitability for cultivation, authors highlight the effects of climate change on agriculture necessitate farmers' adaptation to mitigate these effects (Mikova et al., 2015) Most agricultural activities revolve around seasonal characteristics, leading farmers to choose crops based on available rainfall, as different crops have varying water needs (Kuradusenge et al., 2023).

Inheritance in agriculture involves the transfer of resources across generations (Žutinić & Grgić, 2010). This study's findings corroborate research that accounts for inherited resources in categories such as farmland, agricultural knowledge, skills, practices, farming perceptions, and crops (Saugeres, 2002). Inheritance ensures agricultural continuity and resilience, but it comes with challenges such as conflicts, debt, succession, planning issues, and resistance to new technologies (Bakry et al., 2021; Barnard & Calitz, 2011; Hu & Gill, 2021). Moreover, inheritance may favor male heirs, potentially exacerbating economic inequalities. For families engaged in farming with limited resources, agricultural inheritance can hinder the fulfilment of household needs and modern agricultural technology adoption (Alexandri et al., 2015).

Stakeholders or partners in agriculture, including the private sector, government institutions, and international organizations, play vital roles in supporting smallholder farmers in low-middle-income countries. They provide information, support, and incentives for adopting new crops and farming practices, influencing farmers' decisions to embrace modern and market-oriented agriculture (Vermeulen et al., 2012; Yami et al., 2019). Our findings confirm that farmers have received good seeds of maize and good avocado that are consistently sold to buyers. Private and government involvement in procuring inputs and linking farmers to markets, along with organizations such as *Ejo Hez*a (brighter tomorrow) and *Tubura* (Prosper), further underscores the pivotal role of partnerships in influencing farmers' choices (Sheahan & Barrett, 2014).

4.3 The Livelihood of Farmers

Household food security and nutrition rely significantly on agriculture's essential role. For many families, agriculture is the primary source of sustenance, even for landless individuals who work on other farms (Maithya et al., 2015). These individuals also view agriculture as their primary means of survival, as their compensation may appear in the form of agricultural produce rather than cash, depending on their agreement with landowners.

Families typically cultivate a mix of export crops, cash crops, and food crops to secure food availability throughout the year. Crops do not mature simultaneously, allowing farmers to continuously access food. These diverse crops serve various purposes; some provide sustenance, others generate income, and some serve as a fallback if cash income is delayed (Hashmiu et al., 2022). Most farmers cultivate multiple crops, with those growing cash crops such as tea or Irish potatoes also maintaining food crops such as maize, vegetables, and fruits, often alongside their main crop. Furthermore, households are encouraged to establish kitchen gardens cultivating seasonal vegetables that play a vital role in combating malnutrition, especially among children and mothers (Ahishakiye, 2020).

In many developing countries, agriculture serves as the primary income source for rural households. Similarly, agriculture sustains the livelihoods of around 70% of Rwanda's populace (NISR, 2021a). Farmers sell their crops to cooperatives, consumers, and companies, and the income generated contributes to raising living standards and touching foreign exchange reserves. The Rwandan government has implemented strategies to transform agriculture and alleviate poverty, including agricultural research and development, increased farmer capacity, improved infrastructure, and the promotion of agricultural exports.

Choosing to cultivate specific crops also enables farmers to finance their ongoing farming endeavors. It grants them with access to crucial resources like seeds and fertilizers (Kurdyś-Kujawska et al., 2021). Farmers frequently reserve a portion of their harvest for seed stock in the subsequent planting season. However, the quality of stored seeds plays a crucial role in determining success, as poor-quality seeds can lead to increased costs and risks. Moreover, higher yields from more productive crop varieties allow farmers to maximize their land's potential, leading to increased profits. These higher-yielding crops often require fewer resources, such as water and fertilizer, ultimately reducing production costs (Ali & Talukder, 2008). Additionally, in line with findings observed in diverse countries it is a well-established phenomenon that marketable crops that yield more profit attract buyers willing to pay a premium.

4.4 Challenges in the Choice of Farming

Farmers are laden with challenges that can intertwine and create a tapestry of issues that shape the way the agricultural landscape is managed.

Diseases and pests are significant challenges within the agricultural domain and are responsible for considerable losses and drastic reductions in yields, thereby negatively impacting food security (Kumar et al., 2018). Globally, it is estimated that pests and diseases cause annual losses ranging from 20% to 40%, despite the application of approximately two million tons of pesticides (Simantov, 1980). In Rwanda, this study revealed that pests and diseases, including cassava brown streak, potato late blight, and maize stalk borer (known as Busseola fusca Fuller), are prominent local threats to crop health. Moreover, these pests and diseases not only hinder export earnings and commercial development but also weaken food and nutritional security due to reduced production (Hardwick et al., 2019). Various strategies can be employed by farmers to prevent pests and diseases, with Integrated Pest Management (IPM) being highly recommended, as it encompasses a combination of cultural, biological, and chemical control methods (Stenberg, 2017). Nevertheless, the selection of the method relies on the specific characteristics and extent of the encountered issue (Stenberg, 2017). Thus, it is essential to enhance farmers' organizational capacity to enable them to utilize these methods effectively.

Access to agricultural inputs is another fundamental challenge. Delays in supply, elevated prices, and limited availability impose major constraints on agricultural production, particularly for small-scale farmers. Key inputs include seeds, fertilizers, pesticides, water, machinery, labour, and land (Nabahungu & Visser, 2013). Farmers must also be sufficiently knowledgeable about resource management to ensure environmentally sound practices and increased yields. According to our findings, input supply delays affect the timing of planting, which subsequently affects the overall output. Higher input costs can influence the quantity of inputs used (Liverpool-Tasie et al., 2017). It is crucial to acknowledge that maintaining consistently high levels of production necessitates timely access to all required inputs (Mpandeli & Maponya, 2014). Moreover, the Covid-19 has caused disruptions in accessing agricultural inputs and supplies in numerous countries, further complicating preexisting issues. Certain nations heavily depend on imported farm inputs, in the absence of international aid and domestic effective strategies, countries encounter obstacles in acquiring the necessary agricultural inputs essential for maintaining productivity (Hossain, 2020). To address these issues, a holistic approach that may include input subsidies, fair input markets, training and extension services, and a focus on interconnected factors such as credit, land tenure systems, and marketing can help farmers improve productivity and food security (Schut et al., 2015).

Furthermore, climate-related challenges, such as changes in temperature, rainfall patterns, and soil moisture, significantly impact agriculture (Nkurunziza et al., 2023; Suranny et al., 2022). Participants in our study highlighted excessive sunshine, heavy rains, related hazards, and unexpected rain shortages as major causes of poor harvests. Climate change reduces food production, crop productivity, and threatens global agriculture, food security and nutrition (Kabubo-Mariara & Mulwa, 2019). Moreover, in Rwanda, landslides triggered by increased rainfall have had severe negative impacts on farmers' livelihoods (Bizimana & Sonmez, 2015). Addressing climate-related challenges involves improving agricultural practices, such as planting drought-tolerant crops, efficiently irrigating, and utilizing cover crops for improved soil health. However, it is equally important to strengthen farmers' capacity to manage these challenges effectively. This entails providing accessible climate-smart agricultural education, constructing resilient infrastructure, establishing early warning system and fostering integration into regional or continental mitigation systems. Such measures enable farmers to enhance their adaptation to and mitigation of their detrimental impacts of climate change on their agricultural activities.

Incompatibility between soil conditions and crop requirements represent yet another major challenge for farmers. This occurs when soil conditions are unsuitable for supporting the growth of certain crops. Soil characteristics, including texture, drainage, acidity levels, and nutrient content, can all contribute to this incompatibility (Smita Tale & Ingole, 2015). For instance, beans are sensitive to acidic soil, while sorghum exhibits greater tolerance. Attempting to grow beans in acidic soil may result in stunted growth or crop failure (Soti et al., 2015). Farmers can address soil and crop incompatibility by selecting crops better suited to their specific soil conditions or by improving soil conditions through methods such as liming in acidic soils (Mustafa et al., 2011; Paradelo et al., 2015). However, it is essential to recognize that some farmers may lack access to the necessary resources or knowledge required to manage soil and crop compatibility effectively. Empowering them with the necessary skills and knowledge can significantly enhance crop yields.

5. Conclusions

This study sheds light on the factors influencing farmers' crop choices, the impact of these choices on their livelihoods, and the challenges they face. Farmers in Rwanda base their crop choices on soil and climate suitability, family traditions, household needs, and advice from agricultural partners. Diverse crop choices aim to ensure food security, generate income, and sustain continued farming. These decisions bolster household food security and economic resilience, implying the significance of policies that promote crops diversification. When farmers can generate income and secure their livelihoods, they are more inclined to stay in agriculture essentially for both food and economic prosperity.

However, challenges including pests, restricted access to inputs, climate variability, and soil crop mismatch pose significant obstacles to Rwandan agriculture. Addressing these challenges through targeted interventions and support can improve agricultural productivity and resilience. Agricultural extension services, research, and policies promoting climate smart practices are crucial for aiding farmers in adapting to evolving conditions and enhancing their livelihoods.

6. Limitations and Suggestions

The study acknowledges limitations due to the heterogeneity of the selected study sites, context specificity, limited sample, interpretation complexities and language translation issues. However, it emphasizes the value of qualitative research in agriculture for exploring subjects deeply and understanding farmers' emotions. To enhance generalizability. Future research should include diverse stakeholders in addition to farmers like extension agents and policy makers for a comprehensive understanding of agriculture in developing countries.

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Authors Contributions

The manuscript, led and corresponded by François Xavier Sunday, embodies a collaborative effort reflective of the diverse expertise and contributions of the authors. François Xavier Sunday spearheaded the study design, oversaw data collection, and ensured alignment with scientific and journal standards. Yvonne Uwineza, Ezechiel Ndahayo, and Irene Patrick Ishimwe meticulously drafted the manuscript, while Prof. Lakshmi Rajeswaran enhanced its robustness through revision. Dr. Maryse Umugwaneza provided invaluable advice and mentorship throughout the manuscript's development. All authors approved the final manuscript and agreed to share publication and recognition equally.

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Positional Effects of Bottle-Baited Traps in Reducing Infestation Level of Coffee Berry Borer *Hypothenemus Hampei* Ferrari in Kilimanjaro Region, Tanzania

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Abstract

Coffee berry borer (CBB) is among the key insect pests of coffee worldwide. The use of bottle-baited traps has been in practice in several coffee-growing areas including Tanzania. However, there is limited information about the influence of height and spacing of commonly used bottle-baited traps in managing CBB in coffee-growing areas in the country. Therefore, the objective of this research was to evaluate the effect of height where traps were placed (0.6, 1.2, and 1.6 m) on the reduction of infestation level of coffee berry borers at different developmental stages of coffee fruit (green and red fruit) under field conditions. The experiment followed a completely randomized block design with a factorial arrangement and four replications, three (lower, middle, and upper) levels of height and spacing were placed for 7 months. The number of captured CBB and damaged berries percentage was evaluated. The data were analyzed by R Software (2021) through an analysis of variance and means were separated by Turkey's (0.05). A significant minimum berries damage (0.26%) as an implication of the lowest CBB infestation level was shown at the height of 0.6 m (for all stages of berries). On the other hand, at the red berries stage, the lowest damage (11.12%) was observed at the height of 1.6 m. Generally, this study deduced that the lower the height from which the traps are placed, the lower the infestation level of CBB hence reducing crop damage by the pest.

Keywords: coffee berry borer, bottle baited traps, height, infestation level, developmental stages, crop damage, Tanzania

1. Introduction

Coffee (*Coffea* spp. L. (Rubiaceae)) is the second most-traded worldwide commodity after oil (Zewide, 2021). As an important economic crop, coffee is vital to the livelihood of millions of people globally (Tibpromma et al., 2022). According to Abate 2021 more than 80 countries grow coffee and some countries use coffee as a major cash crop. Among the major two economic coffee species are *Coffea arabica* L. (Arabica) and *Coffea canephora* Pierre ex A. Froehner (canephora). The Arabica has a higher market price due to its organoleptic properties (Gottstein et al., 2021). The organoleptic properties of Arabica coffee such as aroma and flavor are of higher quality which makes it more valuable in the market compared to the other coffee species. In Tanzania, it is estimated that over 320,000 smallholder farmers are responsible for 95% of the coffee production in the country (Kiwelu et al., 2021). Additionally, production has decreased and stagnated in several regions of the nation since the late 1990s, notably the Kilimanjaro region, and has averaged approximately 73,000 tons (FAO, 2021). The infestation of CBB has been playing a significant role in reducing and stagnating coffee production as the industry is still struggling to increase production to 300,000 t (TCB, 2017).

The *Hypothenemus hampei* Ferrari is considered the most significant insect pest in the fields worldwide due to its propensity to reproduce directly inside the developing berries and consequently reduce yield, berries quality, and price of harvested coffee (Vega et al., 2015; Asfaw et al., 2019; Azrag et al., 2020; Lemma et al., 2021). The adult female beetles bore holes into coffee berries and make galleries inside the endosperm, where they lay eggs

(Damtew, 2022; Azrag et al., 2023). The larvae feed on endosperm and consequently damage the seeds. Thus, qualitative losses or circular damage can be due to the low quality of the coffee seeds, as the galleries can allow pathogens to enter, leading to turmoil and spoiling of coffee flavours (Mohob et al., 2022). The *Profenofos* and *chlorpyrifos* are the most efficient and frequently used insecticides in Tanzania (Magina et al., 2016). Still, the use of insecticides has contributed greatly to environmental imbalance and pollution. The pesticide affects CBBs and natural nonentity adversaries and increases the threat that nonentity might develop. Thus, it has threatened communities that live around the coffee fields and increased production costs (Tome et al., 2020; Tunkur et al., 2021; Manson et al., 2022).

The environmentally friendly bottle-baited traps have been designed to reduce the CBB population in the coffee field. The use of traps that are baited with semiochemicals is one of the recognized tools for pest detection and mass-trapping of the female adult coffee berry borer (CBB). The major advantage of using traps is the rapid-fire discovery of the CBB, even when the insect pest density is low during either adult emergence or the movement of adults into the field from neighboring farms for infesting new berries and mating season (Mafra-Neto et al., 2022). The initial CBB captures can be used as an early-warning tool for farmers, to initiate the monitoring before the pest population reaches the economic injury level (EIL) (Sambony et al., 2021). The CBB developmental dynamics relate to indigenous conditions, including coffee phenology, management practices, and climate (Rodríguez et al., 2013). The objective of coffee farmers is the production of high-quality coffee at the best market price produce at a lower cost (Kiwelu et al., 2021). In Tanzania, most coffee is sold in grade-based quality. However, the CBB reduces quality and price, causing losses in yield and increased costs of production.

However, no studies in the country, specifically in Hai district in the Kilimanjaro region, have been done to investigate the proper positioning of bottle-baited traps that may reduce the infestation of this insect pest at different phonological developmental stages of the coffee fruits Arabica and Robusta in coffee fields. Therefore, the objective of this research was to evaluate the effect of height where traps were placed (0.6, 1.2, and 1.6 m) on the coffee fields.

2. Materials and Methods

2.1 Description of Study Site

The field experiments were conducted at Lyamungu Tanzania Coffee Research Institute (TaCRI) Station; Hai district in Kilimanjaro region, located at ($0^o14'41.4353''$S, $37^o14'47.65502''$E) and 1268 m above sea level (m a.s.l.). The site received a total annual rainfall of about 1800 mm per annum and a maximum air temperature ranging from 21.2 to 31 ^oC per year while the average minimum air temperature ranged from 14 to 19 ^oC. The site was selected because it is a hotspot for (CBB) and the presence of a Meteorological Station nearby was another advantage of the site in ensuring the availability of weather data.

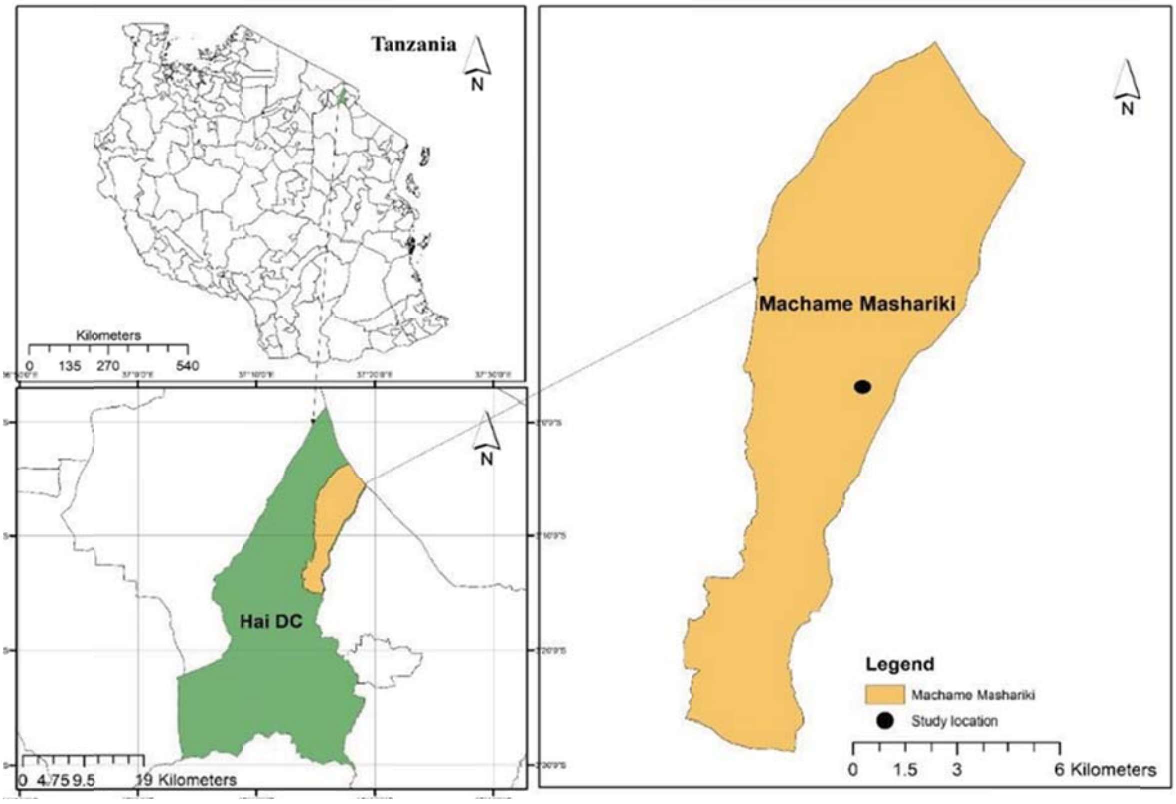

Figure 1. Map showing the study area

2.2 Trap, Dispenser, Counter Machine, and Semiochemicals

The trap used for the experiment was the cheap modified local trap model, developed by a researcher from the Tanzania Coffee Research Institute (TaCRI) to replace the expensive BROCAP® trap (Magina et al., 2016). They were constructed using a recycled empty clear plastic bottle of 1.5 L capacity, with a window opened on two sides (8 × 8 cm). All the traps were painted with red colour half of it to maximize attractiveness to the CBB (Dufour et al., 2019). A dispenser of 30 mL containing semiochemical lure (methylated spirit of 70% alcohol and water) at a ratio of (1:1) v/v having three small opened holes on the rubber cap of the dispenser which allow the semiochemical to evaporate vials those opening for attracting adult female CBB (Magina et al., 2016) was placed inside the trap to the CBBs. Water with detergent 5% was added at the bottom of the bottle to help drown the CBBs adults and other coffee pests captured by the trap. Also, the counter machine was used to count the damaged berries in the coffee field.

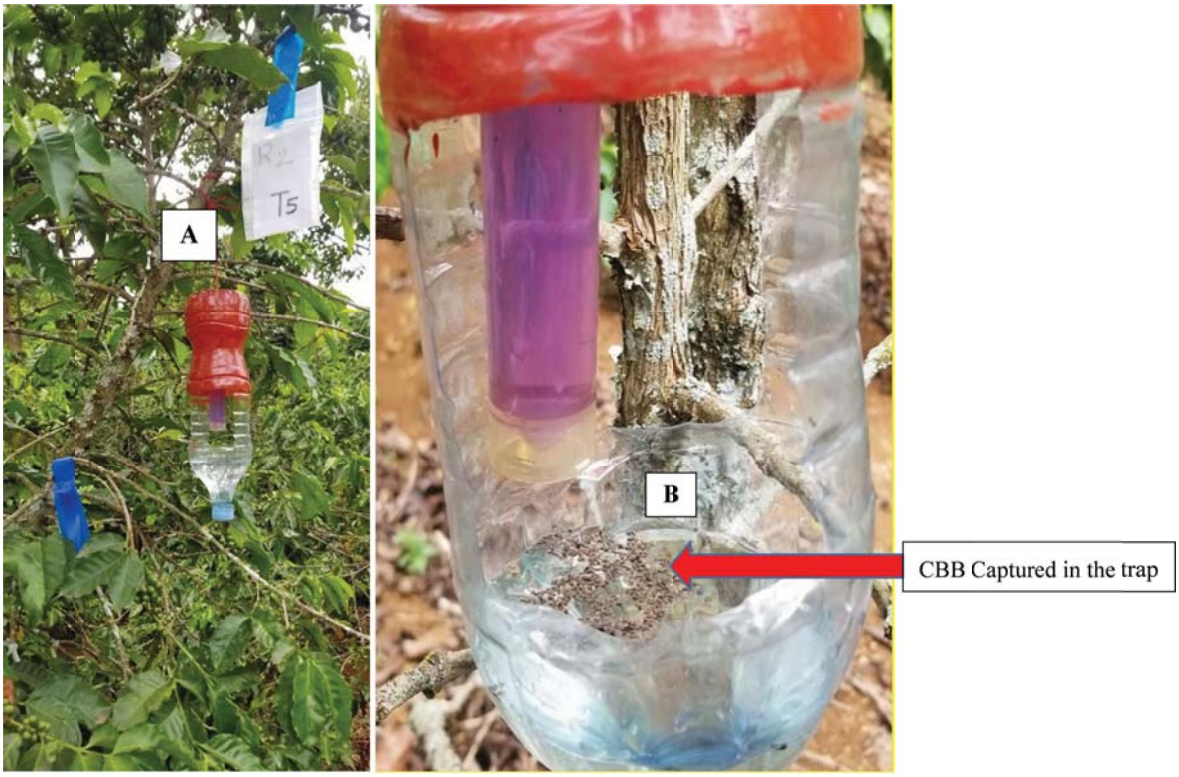

Figure 2. Trap placed in the coffee tree (A) and (B) Coffee berry borer captured in the trap

2.3 Experimental Design

The study used a factorial randomized complete block design (RCBD) with two factors, factor A the trap spacing (distance from one trap to another) in three levels (5 m, 10 m, and 15 m), and factor B was height (from ground level) in three levels (0.6 m,1.2 m, and 1.6 m), making nine treatments which were replicated four times. Four sample trees were randomly selected for each treatment, and two primary branches per height/tree were selected arbitrarily regarding the position lower at 0.6 m, middle at 1.2 m, and 1.6 m upper height of the coffee tree making a total of 2016 branches for fruit phenology observation. Therefore, each branch selected had a minimum of 50 berries.

2.4 Data Collection

The total number of green and red ripe berries with entrance holes, with a pest's damage symptom in the central disc in the selected branches of specific height were counted and recorded every 7 days for 7 months from February to August. Also, the number of (CBBs) attracted and caught in the trap was counted and recorded every 3 days for 7 months consecutively. However, weather variables including rainfall, temperature, and relative humidity were collected at the weather station near the field experiment.

2.5 Statistical Data Analysis

The data on the influences of spacing and height of bottle-baited traps on berry damage by coffee berry borer (CBB) were processed into percentages and then subjected to arcsine transformation before carrying out the analysis of variance (R Core Team, 2021). The means were separated by Turkey's test at a 5% significance level. The Pearson correlation was also done to evaluate the statistical relationship between damaged berries and CBB counts.

3. Results

3.1 Infestation of Coffee Berries by CBB in Relation to Field Positioning of Bottle-Baited Traps

There was a significant effect of the height at which the traps were placed on the percentage of damaged berries (PDB) by CBB ($p = 5.36 \times 10^{-8}$). At a trap height of 0.6 m, fewer berries were damaged by CBB (2.02%), while placing the trap at 1.2 m was related to a higher PDB (5.85%) (Figure 3). However, there was an insignificant effect of the trap's spacing ($p = 0.0964$) as well as the combining effect of the trap's height and spacing ($p = 0.6175$).

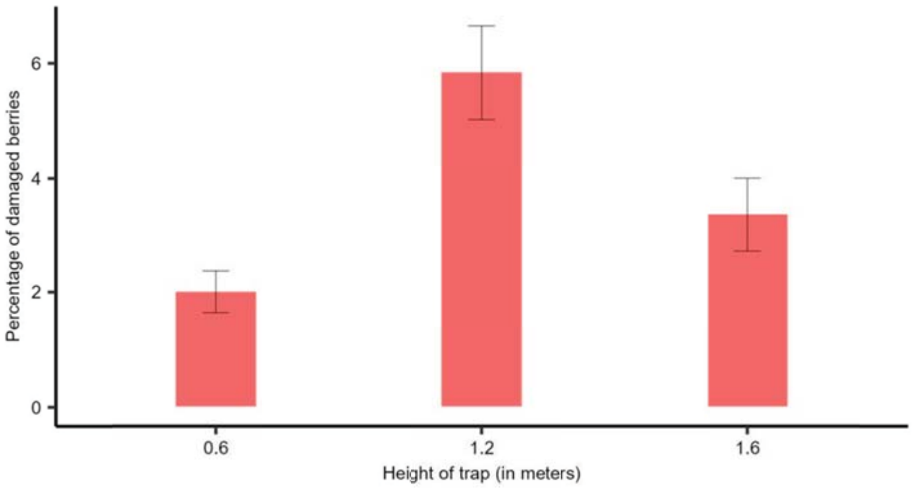

Figure 3. The use of bottle-baited traps at different heights to percentage of damaged berries by CBB

The percentage of damaged berries (PDB) significantly varied as the trap was placed at different trap heights over phonological berry developmental stages ($p = 3.85 \times 10^{-7}$). Minimum damage was recorded at 1.6 m trap height (0.26%) during the red stage of berry development while severe damage was recorded at 1.2 m trap height (11.12%) during the green developmental stage of coffee berries (Figure 4). There was no significant effect of trap spacing ($p = 0.0952$) as well as trap height and spacing ($p = 0.238$) on reducing the berry damage by CBB during the phonological developmental stages of berry.

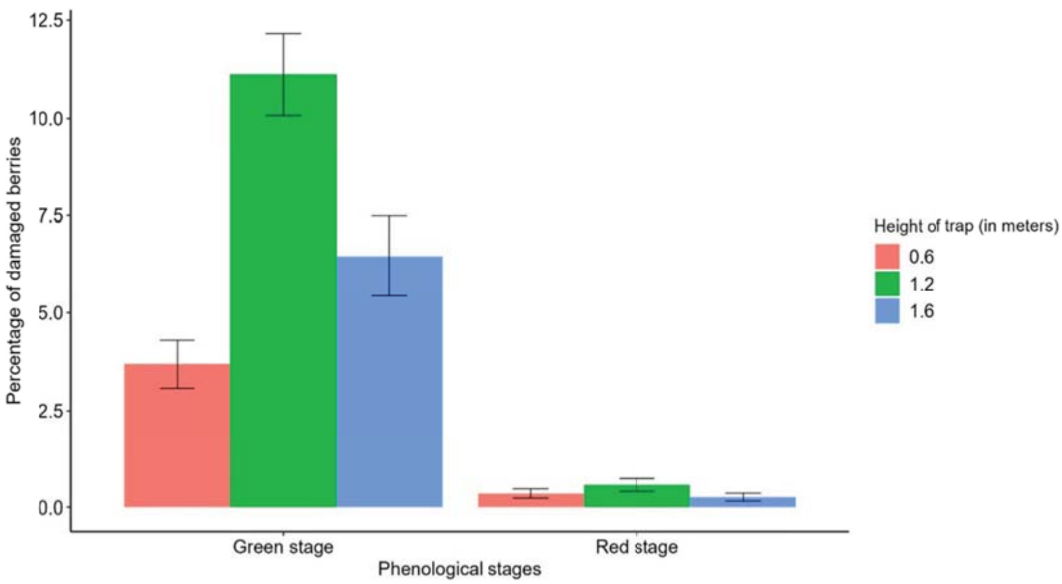

Figure 4. The use of bottle-baited traps at a different height with the percentage of damaged berries by CBB during phonological developmental stages of coffee berries

There was a significant positive statistical relationship between the number of adult CBB and the proportion of damaged berries by CBB during the study period ($r^2 = 0.22$, $p < 0.001$) (Figure 5).

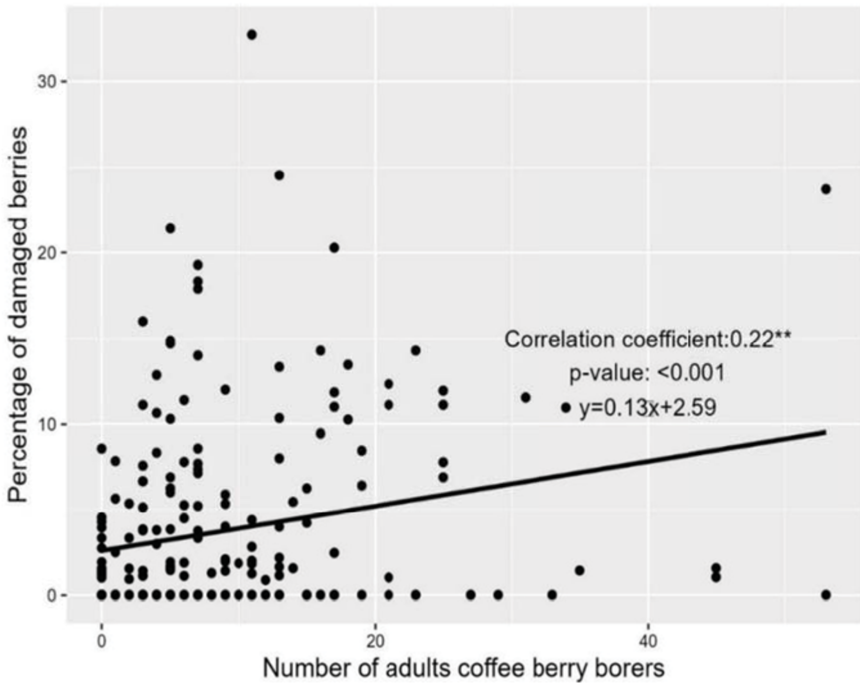

Figure 5. Relationship between the numbers of captured adult coffee berry borer (CBB) and level of infestation (percentage of damaged berries by CBB) in the study area

3.2 Influence of Rainfall, Temperature, and Relative Humidity on the Berry Damage by CBB

The weather information during the experimental period is shown in Table 1. Only temperature and relative humidity showed a significant statistical relationship with the percentage of damaged berries by CBB (Table 1). However, the temperature had a significant positive effect (r^2 = 0.545) while relative humidity had a negative effect (r^2 = -0.331) on the percentage of damaged berries by CBB (Table 1).

Table 1. Pearson's correlation between environmental conditions and coffee infestation by coffee berry borer (CBB)

	Rainfall	Temperature	Relative humidity
Berries damaged	**0.057**	**0.545*** **	**-0.331*** **
Number of adults CBB	**-0.008**	**0.007**	**0.002**

Note. *** Significant at 0.1% level of probability, ** significant at 1% level of probability, and * significant at 5% level of probability.

4. Discussion

4.1 Infestation of Coffee Berries by CBB in Relation to Heights of the Traps

The study revealed that both green and red coffee berries experienced less damage when positioned at a height of 0.6 meters above the ground compared to berries at other branch heights closer to the ground. This phenomenon could be attributed to the concentration of food resources, specifically coffee berries, within the branches of coffee trees situated above the 0.6-m height mark. Likewise, it's possible that the flight behavior of the (CBB) influenced this pattern, as CBBs tend to prefer flying within the range of one to two meters above the ground. This observation aligns with a similar finding reported by Prakoso et al. (2020), which suggests that insects can still be captured in traps positioned up to 1.4 m high, as coffee berries within this height range remain susceptible to infestation.

However, it's worth noting that our findings contradict the results reported by CABI in 2006, which indicated that CBBs prefer to fly in the evening at a significantly higher altitude, around 4-5 m, covering distances of 300-400 m. This discrepancy may stem from variations in environmental conditions or local factors influencing

CBB flight behavior. In light of the study's results, to enhance coffee berry production and quality, it is advisable to position traps at a height of 0.6 m. This approach appears effective in reducing infestation, particularly considering the population density of female adult CBBs (Durfour et al., 2008). Their research demonstrated that traps positioned at a vertical height of 0.5 m within coffee trees captured more adult CBBs, thus contributing to a potential reduction in the overall population density of this insect pest

4.2 Percentage of Damaged Berries by CBB During Phonological Developmental Stages of Coffee Berries at Different Heights

From the results, the minimum percentage of damage was recorded at 1.6 m trap height (0.26%) in the red (ripening) developmental stages of the berries, where numerous berries were inflicted during the period of green stage trap placed at the height of 1.2 m and 0.6 m from the ground. These results might be associated with the presence of berries at that specific height and green stage as preferred more than red because they are easy to penetrate (boring) for making galleries. Likewise, the adult females Coffee berry borer (CBBs) are always attracted to kairomones which are released by developing berries in the coffee field. A similar result was observed by Azrag et al. (2019) in a study where he revealed that adult female feeding injuries on developing fruit (green fruit) lead to berry drop, and offspring feeding galleries in the berry endosperm (coffee seeds) leading to bean dry weight loss and increased vulnerability to diseases infestation.

Furthermore, Asfaw et al. (2019) reported the same, CBBs start and prefer infesting the green stages berries in the field when the dry content of the berry which has to be 20% or higher as this usually acts as a determining factor for the progress of the penetration, also Damon (2000) reported the similar result that Low damage on red ripe berries by CBB regardless of attacking all developmental stages of coffee berries causing a considerable amount of losses. The female usually bore the coffee berry through the disc, originally the floral disc of the flower, the style passes through the floral disc in the flowering stage; during fruit development the hole close up as the style dies back. It has been presumed that the disc is the favourite area for boring as it provides a non-smooth surface for an insect pest to hold on to while initiating the boring process, where the average time to enter the green berry was 4 h and 16 min as reported by (Vega et al., 2015). Regardless of all the developmental stages of the coffee fruit to be attacked, the green berry stage is an important time for placing this trap in the field to avoid the infestation and damage of the berries which can reduce the production and quality of the coffee product.

4.3 The Influence of Temperature and Relative Humidity on the Berry Infestation by CBBs

Along with the positive effect of increasing temperature, we found a negative significant relationship between CBB berries damage and mean relative humidity. This is in line with the findings of several studies that reported temperature and relative humidity as the main abiotic factors positively influencing beetle CBB infestation in the coffee field (Chen et al., 2014). The mean diurnal air temperature was observed in the study to be the single weather variable with the strongest (positive) relationship to CBB damage to the berries in the field. Since insects are poikilotherms, meaning their body temperature in multitudinous aspects of insect biology are driven by temperature including generation length rate of development, mating activities, and dispersal. Thus, the increase in temperature may enhance the production of more CBBs in the area which lead to more infestation of coffee berries in the specific study area. Furthermore, Jaramillo et al. (2011) reported that the thermal conditions necessary for the development of the CBBs range between 13.9 to 15 °C and 25 to 27 °C mean and maximum temperature respectively are optimal for reproduction. The normal range for minimum and maximum temperature at the study site was (14 to 19 °C and 21.2 to 31 °C) which is relevant to the other findings. Moreover, the study done by (Constantino et al., 2021) revealed that infestation of CBBs in the coffee tree was positively correlated with the temperature. Therefore, these changes in temperature favour or limit the biology, development, and emergence of the CBB (Marinol et al., 2016; Johson et al., 2019). Contrary to the study by (Hamiliton et al., 2019) that mentions that the development time of CBB increases with increasing elevation and decreasing temperature, making a negative correlation with CBB damage. An increase in mean temperature is expected in the face of global climate change which may cause changes in insect populations at different altitudinal ranges such as differences in insect-host-plant interaction lags in the synchronization of host insect and parasitoid activity periods and changes to the growth and abundance survival, feeding rates and life cycles of herbivorous insect (Jaramillo et al., 2009; Hil et al., 2011). Therefore knowledge of natural climate variation and the impacts of climate change on insect pests and beneficial insects is important to prevent phytosanitary problems and to develop strategies to adapt to the expected change.

Also, the study showed that relative humidity had negative effects (relationship with CBBs to the berries damage. The negative correlation between CBB emergence and the positive correlation with temperature obtained in this study can be explained by the study of (Hamiliton et al., 2019) which mentions that the development time of CBB increases with increasing elevation and decreasing temperature with the mean requirement. Increase of relative humidity decrease of damage weak correlation and negative correlation.

The CBBs prefer more humidity therefore coffees under shade are susceptible more because they multiply more in such conditions (Damon et al., 2000). Emergence of coffee berry borer from gleanings showed a maximum emergence of borer when the samples were exposed under a natural shower and minimum emergence at 90% relative humidity. This is in confirmation of the earlier result that heavy rain also triggered the emergence of the beetle (Screedharan et al., 1994) and low humidity < 60%, RH 25 °C) provoked rapid evacuation of adults and while it was minimum at 90% RH (Baker et al., 2009). The knowledge that CBB responds to the vertical distribution of the traps also accelerated with some weather variables such as rainfall temperature and relative humidity as reported by Uemura-Lima et al. (2010). The findings presented here are an important first step in exploring plastic baited traps for the protection of coffee from CBB as part of the comprehensive Integrated Pest Management Program.

5. Conclusion and Recommendation

This research found that a plastic bottle-baited trap, placed at a 0.6 m height from the ground always maintained the lowest PDB throughout the study period. Furthermore, the lowest damage in the phonological stage was observed in red berries fruit. Therefore, proper harvesting at the red ripe stage is important to minimize the occurrences of CBB and increase the quality of coffee berries. Furthermore, it is imperative to implement an integrated pest management strategy for the control of CBB especially in the green berries fruit stage as the highest damage inflicted in this stage. Still, similar damage to berries deserves timely and due attention, because the similar huge amount of damage can cause a direct loss in terms of yield quality of harvestable coffee berries.

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Yam Production-Related Agro-climatological Risks and Yam Yield Modeling in Côte d'Ivoire: A Review

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Abstract

In this paper, we present a review of the agro-climatological-related risk of yam production and models developed for yam yield prediction in Côte d'Ivoire. Four official national platforms (Ministry of Agriculture and Rural Development (MINADER), National Center for Agricultural Research (CNRA), National Agency for Rural Development Support (ANADER), Airport, Aeronautical and Meteorological Exploitation and Development Company (SODEXAM)) and six scientific search engines were investigated in this study including Theses.fr, African Journal Online, Science Direct, Google Scholar, WorldCat and Semantic Scholar. Using the boolean parameters "AND", "OR" and "()" to facilitate and direct our search, we were able to define four key phrases comprising the topic words that were used in the search. Exclusion and inclusion criteria for the selection of documents were also defined in advance, as well as the criteria for reviewing and extracting information from selected documents. The results showed that no work in the field of agro-climatological risks related to yam production and yam yield modeling in Côte d'Ivoire was available on these online research platforms at the time of this literature review. However, other studies similar to the scope of this review on yam exist in several West African countries, particularly Ghana, Benin and Nigeria, and also in the Caribbean. These studies use simulation models such as the Approach for Land Use Sustainability (SALUS) model, the Environmental Policy Integrated Climate (EPIC) model and the Cropping Systems Simulation (CROPSYST) model for growth, yield modeling and the influence of climatic parameters on yam. In addition to these models, artificial intelligence through machine learning models was also seen in this review as an excellent tool for yield prediction for several crops including yams.

Keywords: yam production, agro-climatological risks, yam yield modeling, literature review, Côte d'Ivoire

1. Introduction

In recent years, the African continent has experienced longer and more intense heat waves than in the last two decades of the 20th century (Engdaw et al., 2022). In addition, 50% of regional climate projections suggest that these heat waves, which are unusual in current climatic conditions, will be more regular by 2040 or even more severe under the RCP8.5 scenario (Faye, Camara, Diarra, Mboup, & Noblet, 2019). Regarding rainfall, many uncertainties remain: A decrease in rainfall is expected in the Western Sahel while the Eastern Sahel is expected to experience an increase in rainfall. Note that, under the worst-case climate change scenario, a reduction in mean yield of 13% is projected in West Africa (Sultan et al., 2015). Therefore, agriculture is one of the most sectors which are vulnerable to global weather and climate change. In Sub-Saharan Africa (SSA) it is the main occupation and source of income for most of the populations and, therefore, has a great influence on regional food security (Sultan et al., 2013; World Bank Group, 2019). However, the region faces food shortages almost every year due to crop failure or low crop yields (Cedric et al., 2022; Waongo, 2015). According to these authors (FAO, 2015, 2017; Raes et al., 2018), the use of adapted varieties or breeds, with different environmental optima and/or broader environmental tolerances, including currently neglected crops, also considering that increased diversification of varieties or crops is a way to hedge against the risk of individual crop failure. Among these crops' failure, there is the yam which is the second most important root/tuber crop in Africa after cassava (Lebot & Dulloo, 2021). Yams (*Dioscorea* spp.) are extremely important to food security because of their excellent storage properties; they can be stored for four to six months without refrigeration and provides an important food safety net between growing seasons. They are a staple food for millions of people in tropical countries and provide pharmacologically active compounds for traditional medicine and the pharmaceutical industry (Adifon et al., 2019; Andres et al., 2016; Neina, 2021). Yams are grown in about 50 tropical countries, not all of which provide their annual production statistics to the United Nations Food and Agriculture Organization. Annual world production is about 72 million tonnes of fresh tubers. More than 98% of this production is grown in Africa, with only four countries (Nigeria, Côte d'Ivoire, Ghana and Benin) accounting for 93% of this production (Lebot & Dulloo, 2021). Particularly, Yams are widely grown in Côte d'Ivoire, and among food crops, yam is the most cultivated (BCEAO, 2017; Diarrassouba, 2019; MINADER, 2017). It is therefore a crop that has a choice place in the Ivorian economy and food and nutritional security. The landrace varieties *Kponan*, *Krengle*, and *Djate*, are in high demand, as are the improved varieties TDA, Mao and C20. The latter have demonstrated good productivity, disease resistance and drought tolerance.(Adifon et al., 2019; Kouakou et al., 2019; Michel & Apata, 2017). Despite all these assets, yam production is facing challenges due to several issues. Planting and harvesting are labour-intensive, yield and postharvest durability vary significantly with soil quality and climactic factors, decreasing soil quality and mounting pest pressures, rotting of seedlings in the mound due to high surface temperatures, the false start of the rainy season and the failure to update agricultural calendars according to rainfall variability are among the causes faced by farmers and the yam sector in Côte d'Ivoire (Anogbro, 2015; Frossard et al., 2017; Kouakou et al., 2019; World Bank Group, 2019). So, it requires continuous monitoring to improve crop yields (Kosamkar & Kulkarni, 2019). Given the changing climate, predicting scenarios and crop yield based on models will help increase production, forecast the growing season, take adaptive measures and allow farmers to be more resilient (Fayaz et al., 2021; Kosamkar & Kulkarni, 2019; Malhi et al., 2021). Note that, at the national level in the literature about yam cropping, almost all the studies done by researchers are in biology, genetics, physiology and the marketing of yam area. Some climate variabilities are also studied, highlighting the impacts of the latter (Anogbro, 2015; Doumbia et al., 2006; Kouakou et al., 2019; Valerie, 2012). For this reason. in this paper, we present a review of the agro-climatological-related risk of yam production and models developed for yam yield prediction in Côte d'Ivoire. Crop models are an essential tool for studying the impact and potential adaptation options in root and tuber production. A crop model consists of mathematical equations that describe the development and growth of the crop over time, based on environmental factors (Cedric et al., 2022; Fayaz et al., 2021; Raymundo et al., 2014). Crop models use crop characteristics, climate data and soil characteristics to simulate crop responses to management practices and various environmental conditions. Crop models can be used to anticipate the effects of climate change on root and tuber production (Degila et al., 2023; Raymundo et al., 2014). In this study, we will evaluate the existing models that have served as a study of yam in Côte d'Ivoire through scientific search engines, online documentary databases and national reports. The general differences, their structures, similarities, limitations and applications in the field of climate change and research gaps have been discussed.

2. Material and Methods

2.1 Presentation of Côte d'Ivoire

Côte d'Ivoire is located between Longitudes 2°30′ and 8°30′ W and Latitudes 4°30′ and 10°30′ N with an area of 322 462 km^2, covering about 1% of the African continent. It is part of West African countries sharing borders with Liberia and Guinea to the West, Mali and Burkina-Faso to the North and Ghana to the East part (Figure 1). The South part of the country is covered by the Atlantic Ocean with a 550 km long coastline (Kouame et al., 2020). The central and coastal areas each have four seasons: April to mid-July: a long rainy season, with frequent rainfall and numerous thunderstorms; mid-July to September: a small dry season, the sky can remain overcast; September to November: a short rainy season, with some light rainfall; December to March: high dry season. The northern zone has two seasons: the period from June to September is the rainy season and the period from October to May corresponds to the great dry season (Kouame, 2021; Kouame et al., 2020).

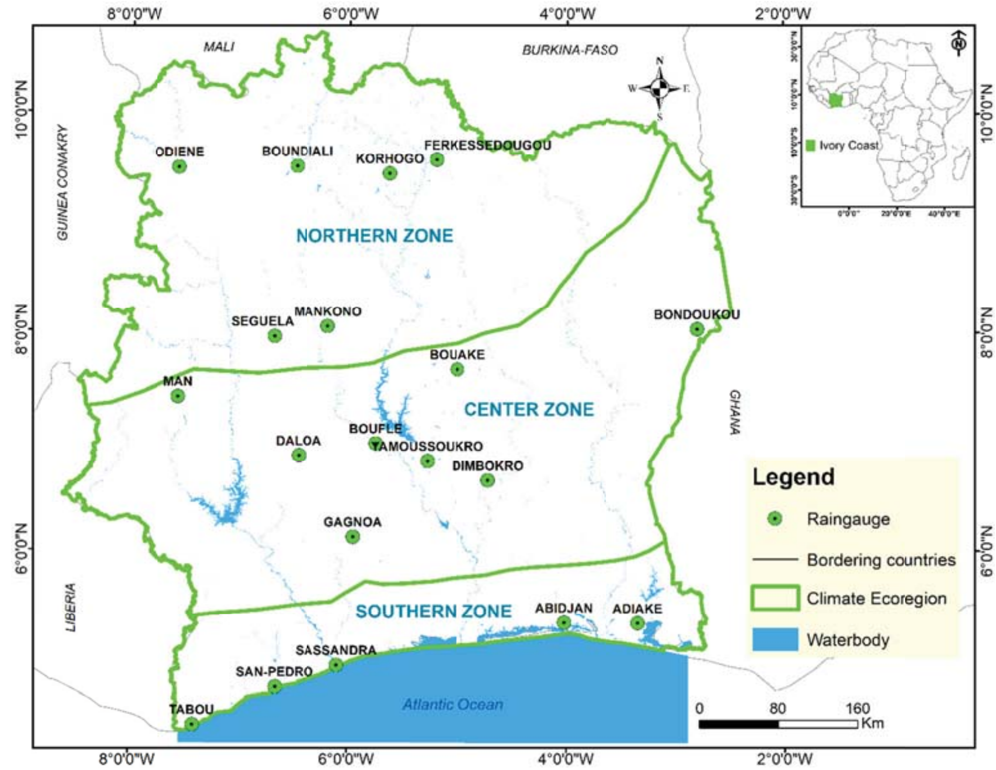

Figure 1. Distribution of the rain gauges and climatic division depending on rainfall patterns in Côte d'Ivoire

Source: Kouame et al. (2020).

2.2 Research Methodology

This study was carried out in the framework of a literature review of existing studies, systematic reflection, and scientific journals/reports to highlight the approaches already done and available results relating to yam production-related risks and yam yield modeling in Côte d'Ivoire. We searched tools, methods, data used and results reported in the literature. Several documents, such as articles, national reports and peer reviews, were considered in this study. In order to achieve this, we referred to Boolean terms (Dahan & Kasei, 2022; Kohl et al., 2018; Ouattara et al., 2023; Tran et al., 2023). Boolean operators (sometimes called Boolean terms or commands) connect the keywords to create a logical phrase that the database can understand. This involves telling the database to look for multiple terms or concepts at once, which makes the search more precise (Kohl et al., 2018; Pušnik et al., 2022; Snyder, 2019). The Boolean operators used in this research are "AND", "OR" and "( )" (Table 1).

Table 1. Boolean operators: "AND", "OR" and "( )"

Boolean operators	What it Does
AND	Find items that use **BOTH** keywords.
OR	Find items that use **EITHER** of the keywords.
Brackets ( )	**GROUP** multiple search strings and **SET PRIORITIES**

For the purpose to exploit the boolean operators, and search for the necessary data to complete this study, four (4) official websites of Ivorian institutions in charge of agriculture for some and climate for others (**Table 2**) and six (6) scientific search engines for online documentation (**Table 3**) were defined and consulted individually. This makes a total of ten (10) information sources defined for this review.

Table 2. Official websites of Ivorian institutions

	Institutions names	Websites
1	Ministry of Agriculture and Rural Development (MINADER)	https://www.agriculture.gouv.ci/
2	National Center for Agricultural Research (CNRA)	https://cnra.ci/
3	National Agency for Rural Development Support (ANADER)	http://www.anader.ci/
4	Airport, Aeronautical and Meteorological Exploitation and Development Company (SODEXAM)	https://www.sodexam.com/

Table 3. Scientific search engines

	Platforms	Website*	Purpose and country	Launch year
1	Thesis search engines	https://www.theses.fr/	It is a search engine to find French doctoral theses. Based in French	Jul. 2011
2	African Journals Online	https://www.ajol.info/index.php/ajol	Provides access to African-published research, and increases worldwide knowledge of indigenous scholarship. Includes 38 African countries including Côte d'Ivoire	1998
3	Science Direct	https://www.sciencedirect.com/	Provides access to a large bibliographic database of scientific and medical publications of the Dutch publisher Elsevier. It hosts over 18 million pieces of content. Based in Netherlands	Mar. 1997
4	Google Scholars	https://scholar.google.com/	Google Scholar is a freely accessible web search engine that indexes the full text or metadata of scholarly literature across an array of publishing formats and disciplines. Based in USA	Nov. 2004
5	World Catalogue	https://www.worldcat.org/	WorldCat is a union catalogue that itemizes the collections of tens of thousands of institutions (mostly libraries), in many countries, that are current or past members of the OCLC (USA nonprofit cooperative organization) global cooperative. Based in USA	Jan. 1998
6	Semantic Scholar	https://www.semanticscholar.org/	Semantic Scholar is an artificial intelligence-powered research tool for scientific literature developed at the Allen Institute for Artificial Intelligence (AI). Based in USA	Nov. 2015

Note. *: These information sources can be found on the above websites.

2.3 Document Search

This phase consisted of a search strategy for the documentation. The search strategy allowed us to define an appropriate search string based on the relevant databases identified and defined in the previous Tables 2 and 3. The number of articles included in the final analysis was influenced by the search criteria defined in Table 4. Furthermore, the definition of the search string was based on the topic terminologies. The search string is listed focusing mainly on "Yam production-related agro-climatological risks" and "Yam yield modeling in Côte d'Ivoire" with the addition of Boolean operators (Tables 5 and 6). The search terms were performed separately or in limited combinations that took into account the requirements or limitations of the database used (Mengist et al., 2020). In these databases, publications that were not downloaded for further study were discarded. The articles were peer-reviewed journals from the seven data sources and the literature searches were finalized on 19 May 20023. The search was conducted in these different internationally recognized databases to collect relevant information from the publications (Gonçalves et al., 2018). These are all international databases of peer-reviewed publications from around the world (Gonçalves et al., 2018; Mengist et al., 2020). Besides, the size and types of databases used to search for publications helped determine the size of the sample drawn for examination. Note that the research on the national platforms was done both in English and French, the latter being the country's (Côte d'Ivoire) official language.

Table 4. Selection of literature using inclusion and exclusion criteria

Criteria	Decision
When the predefined keywords exist as a whole or at least in the title, keywords or abstract section of the paper.	Inclusion
The paper was published in a scientific peer-reviewed journal.	Inclusion
The paper should be written in the English or French language.	Inclusion
Studies presenting evidence on crop modeling/climate impact studies on yam.	Inclusion
When the articles address at least one agro-climatological indicator.	Inclusion
Papers that are duplicated within the document search engines.	Exclusion
Papers that are not accessible, review papers and meta-data.	Exclusion
Papers that are not primary/original research.	Exclusion
Papers published before 1998.	Exclusion

Source: Adapted from Mengist et al. (2020).

Table 5. The search terms used and the total number of publications from the country databases

Databases	Databases Searching string and searching terms		No. of papers	Date of acquisition
MINADER	Main searching terms	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Secondary searching terms	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Tertiary searching terms	Yam production-related agro-climatological risks (Côte d'Ivoire)	00	5/19/2023
	Fourth searching terms	yam yield modeling (Côte d'Ivoire)	00	5/19/2023
CNRA	Main searching terms	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Secondary searching terms	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Tertiary searching terms	Yam production-related agro-climatological risks (Côte d'Ivoire)	00	5/19/2023
	Fourth searching terms	yam yield modeling (in Côte d'Ivoire)	00	5/19/2023
ANADER	Main searching terms	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Secondary searching terms	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Tertiary searching terms	Yam production-related agro-climatological risks (Côte d'Ivoire)	00	5/19/2023
	Fourth searching terms	yam yield modeling (in Côte d'Ivoire)	00	5/19/2023
SODEXAM	Main searching terms	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Secondary searching terms	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	00	5/19/2023
	Tertiary searching terms	Yam production-related agro-climatological risks (Côte d'Ivoire)	00	5/19/2023
	Fourth searching terms	yam yield modeling (in Côte d'Ivoire)	00	5/19/2023

Table 6. The search terms used and the total number of publications from scientific search engines

Databases	Database searching string and searching terms		Searching matches	No. of papers	Date of acquisition
Thesis search engine	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire		00	5/21/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire		00	5/21/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)		00	5/21/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title. Just one keyword	11	5/21/2023
African Journals Online	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire	Searching terms don't match any title. Just some keywords	16	5/19/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	Searching terms don't match any title. Just some keywords	36	5/19/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)	Searching terms don't match any title. Just some keywords	42	5/19/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title. Just some keywords	76	5/19/2023
Science Direct	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire		00	5/21/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	Searching terms don't match any title. Just some keywords	298	5/21/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)		00	5/21/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title. Just some keywords	268	5/21/2023
Google Scholar	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire		00	5/20/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire		00	5/20/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)		00	5/20/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title. Just some keywords	8,790	5/20/2023
World Catalogue	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire		00	5/20/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire	Searching terms don't match any title, any keyword	02	5/20/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)		00	5/20/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title, any keyword	02	5/20/2023
Semantic Scholar	Main	Yam production-related agro-climatological risks AND yam yield modeling in Côte d'Ivoire		00	5/20/2023
	Secondary	Yam production-related agro-climatological risks OR yam yield modeling in Côte d'Ivoire		00	5/20/2023
	Tertiary	Yam production-related agro-climatological risks (Côte d'Ivoire)	Searching terms match only some keywords	05	5/20/2023
	Fourth	Yam yield modeling (in Côte d'Ivoire)	Searching terms don't match any title. Just some keywords	126	5/20/2023

3. Documents Analysis

The information extracted from the documents was analyzed qualitatively based on different criteria and categories (Table 7). This objective analysis was done to ensure the viability and authenticity of the data source used in the papers collected (Dahan & Kasei, 2022; Gonçalves et al., 2018; Manikas et al., 2023; Mengist et al., 2020; Snyder, 2019). After a sufficiently thorough reading of the various documents, the information relevant to this study was extracted according to the criteria and categories captured in Table 6 below.

Table 7. The criteria used for extracting information from the selected papers

No	Criteria	Categories considered	Justification
1	Document types	Official papers/articles/reports/thesis	from one of the ten (10) sources defined for this review is considered
2	Year of publication	Between 1998 and Mai 2023	The year in which the oldest journal goes online is considered
3	Study area	Country	-
4	Types of data sources	Primary data	Data derived from sampling in the field (*e.g.*, field data, surveys, interviews or census data)
		Secondary data	Data not verified in the field (*e.g.*, remote-sensed data, a bibliography, modeling, socioeconomic data)
		Mixed data	Mixed both above sources
5	Methods	Cultivar and soils types; Climate indices; statistics relationships; models used.	Incorporate existing knowledge to link with Yam models, climate models and Yam production-related agro-climatological risks.
6	Mode of assessment	Qualification, quantification, or both	Expressing climate and agriculture values with verbal terms or using numbers mathematics expressions or both
7	Difficulties mentioned	Methodological	Uncertainties on the result due to the application of the unclear or less developed method; Uncertainties linked with lack of conceptual clarity.
		Data analysis	Data analysis skills and the choice of suitable tools can challenge the work.
		Lack of model validation	Most crop modeling studies lack to verify the results using model validation.

4. Results and Discussion

4.1 Review of the Search Performed

4.1.1 National Platforms Search Engines

On the National platforms, none of the four (4) revealed a single trace of documents or research available. This could mean that no studies in this or a related field have been carried out and are available. It could also mean that the documents of the works are published elsewhere either than the platform or that the works are kept in hard copies in the libraries of these structures.

4.1.2 Theses.fr Search Engine

At the level of the Theses.fr platform: only eleven (11) documents were found in all the searches. It is the fourth searching term [*yam yield modeling* (*Côte d'Ivoire*)] that allowed us to have this result. The search was carried out by selecting all the possible search options available on the website, including 'defended theses only' and 'defended and online theses', and the year, which by default is defined as the broadest possible on the website 'before 2013 to 2023'. Thus, none of these 11 documents were selected according to the inclusion and exclusion criteria established beforehand. Indeed, the search terms do not appear at any level in the titles of the documents nor the keywords, but it should be noted that this French PhD platform provides a wide range of related fields in addition to what is requested.

4.1.3 AJOL Search Engine

On the AJOL databases, 181 papers were found across all four search terms. Among these documents, the most relevant ones deal with climate change for some and yam production for others, but in other countries. None of these papers address the issue of yam yield modeling in Côte d'Ivoire, or elsewhere. In fact, AJOL displays from its database the documents available according to the search terms used, including those that have nothing to do with the topic. As I read on, I realized that AJOL relies on the search terms found in the abstract of certain documents to suggest search results. This is why we had 170 documents and none of them were useful for our intended purpose.

4.1.4 Science Direct Search Engine

The research was successful in that we obtained five hundred and sixty-six (566) results from all four searches. With Science Direct, we were able to detect some documents that deal with our topic elsewhere in other countries. We have kept these documents for further analysis. It should be noted that synonyms for certain keywords such as ‘modeling’ were found in the form of ‘simulation’. Moreover, we were able to find these words in the same document: ‘*Simulating*’, ‘*yield*’, ‘*yam*’ and also these words: ‘*Modeling*’, ‘*yam*’, ‘*yield*’ in the same document. Some of these works whose association with these keywords were carried out in West African countries like Benin Republic and Ghana. In these documents, after analysis, it can be seen that some models have been used to effectively simulate yam yield. We note: Environmental Policy Integrated Climate (EPIC) model (Srivastava & Gaiser, 2010) and the Systematic Approach for Land Use Sustainability (SALUS) model (Liu et al., 2021).

4.1.5 Google Scholar Search Engine

On Google Scholar, no document was found after the three first search terms. In the last search terms, we got eight thousand seven hundred and ninety (8,790) results. All the key works were found but not in the same document. We applied three successive filters to select the most relevant ones using quotation marks (“ ”). The first was: [*yam yield* “*modeling*” (*Côte d’Ivoire*)], the second was: [*yam* “*yield modeling*” (*Côte d’Ivoire*)] and finally, the third was: [“*yam yield modeling*” (*Côte d’Ivoire*)]. Successively, the result went from 8,790 to 2,390 then to 08 and then to 00. One of the documents in which we can find keywords that Google Scholar provided is entitled: Simulating cocoa production: «A review of modeling approaches and gaps. But unfortunately, it does not address the subject of yam. It should be noted that Google Scholar is one of the most widely used scientific search engines worldwide and is accessible to all researchers for the promotion and enhancement of research. Therefore, the absence of a relevant document in Google Scholar implies If despite this fact, no relevant document has been found, there is reason to believe that the work has not yet been studied in Côte d’Ivoire.

4.1.6 WorldCat Search Engine

On WorldCat, the world’s largest library catalogue, our searches yielded four (4) results in all especially two in the second and two in the fourth search terms. However, after analysis, there were the same two documents found in each search. These documents do not contain any of the keywords of our research, neither in the titles nor in the abstract keywords.

4.1.7 Semantic Scholar Search Engine

On Semantic Scholar, our searches yielded a hundred and thirty-one (131) results in all search terms. It includes all the keywords but all of them were found in the fourth search individually in different documents that do not necessarily deal with yams. An example of a topic: “Potential Impact of Climate Change on the Sediment Fluxes of a Watershed in West Africa”. The other is: “Modeling greenhouse gas emissions of cocoa production in the Republic of Côte d’Ivoire”. You understand that these are the most relevant of the 126 documents but are not useful because they do not address the cases we are looking for. However, Semantic Scholar is a powerful search engine with over 200 million papers from all fields of science. The best part is that it is free to access and all papers are open access to download with all possible metadata with redirections to other topics of interest depending on the papers downloaded.

Below is a screenshot of the search performed in each scientific search engine with the main search term which is: [*Yam production-related agro-climatological risks AND yam yield modeling in Côte d’Ivoire*] (Figure 2).

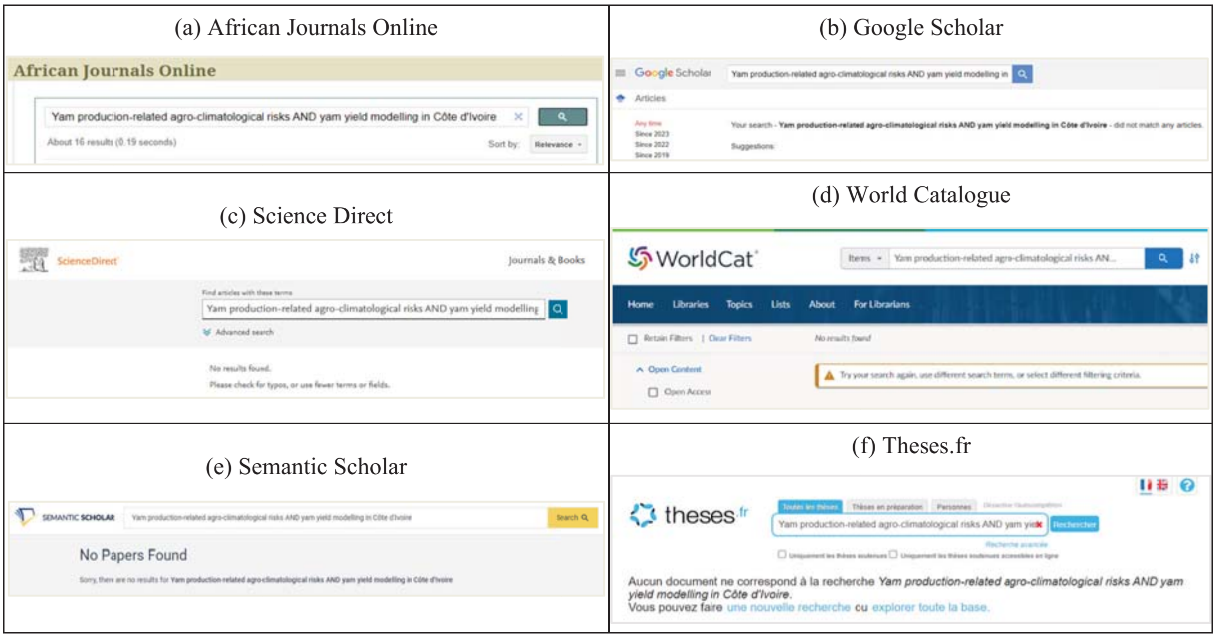

Figure 2. An example of a screenshot of each research performed using the main search terms in scientific search engines

4.2 Outcomes Using Inclusion and Exclusion Criteria

By applying the inclusion and exclusion criteria, papers that fulfill the inclusion criteria were selected for further investigation and content assessments. Unfortunately, no papers dealing with the subject we are discussing have been selected for Côte d'Ivoire. The predefined literature inclusion and exclusion criteria to achieve this review work were presented in Table 4. It is important to add that papers like grey literature, extended abstracts, presentations, keynotes, and research work that is not original and duplications were omitted. Figure 3 shows the flowchart diagram of our research according to the exclusion and inclusion criteria.

4.3 Related Work

The related work section focuses on literature reviews involving the eligibility documents. As no studies in our field of research have been carried out in Côte d'Ivoire, we have turned to eligibility documents for further analysis to find out more about what is being done at this level in the West African sub-region or elsewhere. Indeed, related works have been done in Benin Republic, Nigeria and Ghana according to the eligibility papers (08 documents) in Figure 3. These countries are all Sub-Saharan West African coastal countries with the same hot and humid tropical climate. We have therefore used the results of this research to find out exactly what has been done and to explore the possibilities of transferring technology from these findings to the local level in Côte d'Ivoire following Table 7 categories and criteria for the analysis. Crop yield modeling is one of the most important elements of agricultural decision-making today. Crop system models are therefore valuable tools to inform agronomic decisions and advance research. The prediction accuracy of simulation models is one of the most vital components in yield modeling.

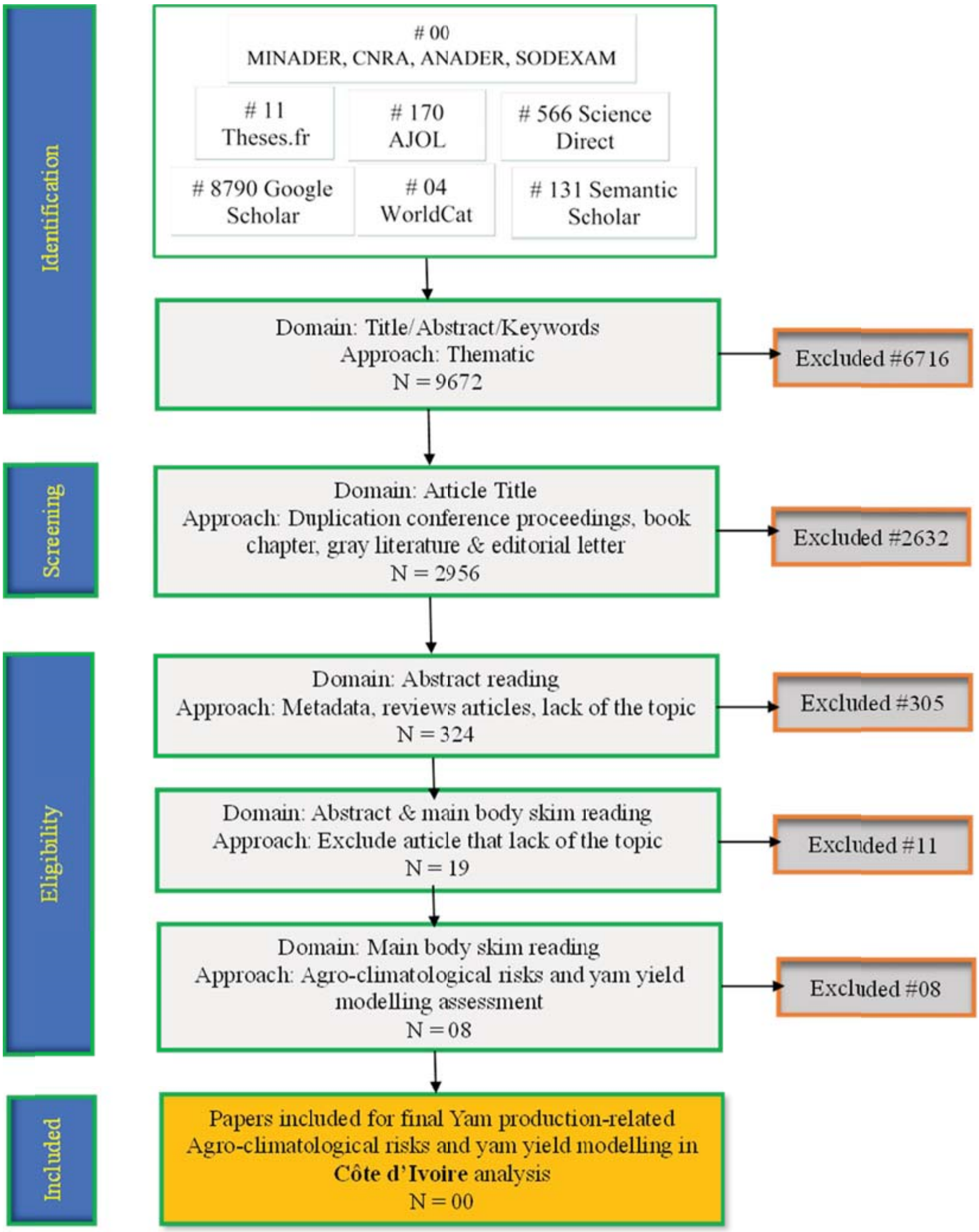

Figure 3. Flowchart diagram for databases search of documentation for reviews and the results found

Source: Adapted from Mengist et al. (2020).

The basic operating mode of crop models requires input data such as soil, climate, plant and management which is used by crop simulation model for predicting the crop yield (Figure 4) and describe the process of growth and developmental stages of crops (Dzotsi et al., 2013; Kosamkar & Kulkarni, 2019; Srivastava et al., 2012).

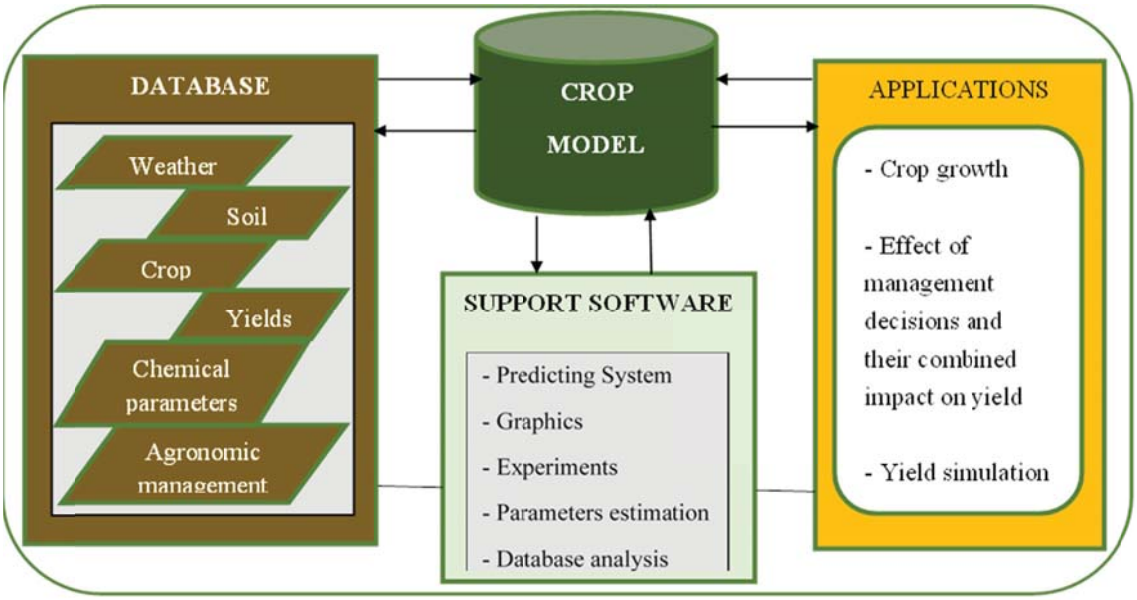

Figure 4. Crop modeling operating system

Source: Adapted from (Dzotsi et al., 2013; Jones et al., 2003; Srivastava et al., 2012).

4.3.1 Yam Yield Modeling Approaches

In their work, these authors (Liu et al., 2021; Marcos et al., 2011; Srivastava et al., 2012; Srivastava & Gaiser, 2010) studied yam yield modeling, water yam (*Dioscorea alata* L.) growth and the prediction of yam productivity under different agronomic management. Table 8 below summarizes the details of their modeling approaches. Several yam-adapted crop models and machine learning techniques have been used for yam modeling across Africa and the Caribbean (French Antilles).

Table 8. Summary of the approaches to Yam yield modeling

Study area/ Models used/ Authors and year	Inputs data	Parameterization/ Statistical analysis/ Model evaluation	Outputs modules
Ghana/ Approach for Land Use Sustainability (SALUS) model/ (Liu et al., 2021)	- Yam parameters for the model were based on reported values in the literature and the calibration processes; - Crop coefficients and management (planting dates, fertilizer, irrigation water, and tillage); - Soil data (organic C, total N, bulk density, clay, and silt) derived from the Africa Soil Information Service (AfSIS) database includes soil layer parameters The gridded soil profile resolutions were 1 km and 250 m; - Weather data including min-max temperature, precipitation, and solar radiation from the gridded 0.5∘-resolution POWER dataset and also from stations at the two locations of the study.	- Use of field observations and compare the simulated phenology and biomass (both tuber yield and aboveground biomass) to the field observations from two different locations to parameterize the SALUS-Yam model; - Root mean square of deviation (RMSD) and mean absolute percentage error (MAPE) used to evaluate SALUS-Yam model accuracy; - Outputs modules evaluations were based on comparisons between observed and simulated data applied to the crop model.	- Soil Organic Carbon (SOC) and yield response under the different agro-ecological zone soil types, and changes in nutrients and water; - Simulation of yam phenology and biomass response to N and P fertilizer; - Two major sources of uncertainty were observed: soil and weather inputs.
Benin Republic/ Environmental Policy Integrated Climate (EPIC) model/ (Srivastava et al., 2012; Srivastava & Gaiser, 2010)	- Data for the model calibration including rainfall distribution, crop characteristics (aboveground biomass, tuber yield, LAI, etc.) and soil properties (moisture retention properties, chemical composition, etc.) were obtained on-farm trials at Dogue village; - Crops parameters values were derived from four sources: experiments, cassava parameter file from EPIC (version 3060), literature and the adjusted value.	- The mean residual error (ME) and the mean absolute error (MR) were used to compare observed data and simulated values; - The EPIC model performance was evaluated by comparing the simulations of 2 years' worth of yam yields with an experiment from Dogue village and by determining the coefficient between the observed and simulated yield of yam.	- Simulation of yam growth and the effect of fertilizer on yam yield; - Yam (*D. alata*) growing conditions in sub-humid tropical savannah areas.
Guadeloupe/ Cropping Systems Simulation (CropSyst) model/ (Marcos et al., 2011)	- Two independent data sets from field experiments under non-limiting conditions for water and nutrients and over a wide range of planting dates and photoperiods including Mean temperature (∘C), Mean global radiation (MJ m^2 d^{-1}), Mean photoperiod (h), Planting date and years of the experiment; - Rainfall data (annual rainfall for each year) from the Experimental Station of Duclos; Soil data, yam yield (variety Lupias); - 200g of fresh biomass was used for the yam planting.	- Calibration of the model and test of the model were based on comparisons between observed and simulated data from Experiment 1 and Experiment 2; - Determination coefficient (R^2) and Root Mean Square Error (RMSE) were used to determine the best fit of parametrization of the model and to evaluate the two Experiments conducted.	- Change in the Radiation Use Efficiency (RUE) as a function of the planting date; - RUE effect on yam growth and yields; - Yam development and growth; - Vegetative and Tuberisation phase, Total biomass and Yam yield from the two Experiments (1 and 2) were compared.
West African countries/ Machine learning, models-based decision tree/ (Cedric et al., 2022)	- Crop yield, annual rainfall, temperature, pesticides and chemical data from 1990 to 2020 from nine West African countries collected from the Food and Agriculture Organization for the United Nations and the Climate Knowledge Portal World Bank; - Analysis parameters: Yield (kg/ha), Temperature (K), Pesticide (t), Rainfall (mm), NO_2 (1018 µg).	- Crops Multivariate Logistic Regression (CMLR), Decision tree, and k-Nearest neighbor algorithm as machine learning algorithms for modeling processing; - Pearson Correlation between features (NO_2, Temperature, Rainfall, Pesticide, Yields, Years); - Use three metrics to evaluate the models: Determination coefficient (R^2), Mean Absolute Error (MAE) and the Run-Time of each model.	- Illustrations of the main parameters influencing the six crop yields: rice, maize, cassava, cotton, yams, and bananas; - Prediction of each crop yield.

4.3.2 Impact of Climate Change on Yam Yield

Climate change has the potential to significantly impact yam production through soil degradation, increasing the incidence of pests, and diseases and creating yam tuber beetle, and changes in rainfall patterns. As yam is a rainfed crop, hence, changes in rainfall patterns can significantly impact its production. According to a study by the World Bank Group (2019), these effects due to climate change lead to decreased yam yields in Côte d'Ivoire. Also, sorting out issues relating to yam production in Nigeria, authors conducted a study forecasting the effect of climate variability on yam yield in rainforest and guinea savannah agro-ecological zone of the country. They used secondary data sources including the climatic data variables, yam area cultivated and yam output in their study (Adeleke Aturamu et al., 2021). The results of the study showed that rainfall and temperature are changing over time and unpredictable. Using the Representative Concentration Pathway (RCP), yam yield for 2050 was predicted to be 0.34mmt/ha and 0.21 mmt/ha under RCP 4.5 and RCP 8.5 scenarios respectively. Over time (2030, 2040 and 2050) in the rainforest Agro-ecological zone (AEZ), yam yield is expected to be negative under both RCP scenarios (RCP 4.5 and RCP 8.5) (Table 10). Furthermore, in the savannah zone of West Africa, Srivastava et al. (2012) addressed the global climate change impacts on tuber crops by using a simulation approach to assess the long-term regional-scale changes in yam production under A1B and B1 IPCC SRES scenarios. They did not stop only that, better, they were able to examine the vulnerability of yam to climate change in conjunction with the soil conditions. The methodology, data and approaches used are recorded in Table 8. Concerning their findings, they concluded that the impact of climate change under the A1B IPCC SERES scenario on yam production is significant and will be protuberant in the 2040s. Concerning the soil type, S1 (Ferruginous soils impoverished without concretions) seems to be the most sensitive to climate change followed by S2 (Ferralitic soils) and S3 (Raw mineral soils) (Srivastava et al., 2012). Still on the effects of climate variability on yam production, a study was conducted in the Nothern part of the Benin Republic by Adifon et al. (2020). Their study shows that the agro-climatic stress index (ASI) and the annual rainfall are the main climatic factors which determine the yield of yam in the various growing areas in Benin. He was also able, through a field survey among yam farmers, to gather their perceptions of yam production conditions and the challenges they face. The survey revealed that yam farmers are unanimous about the influence of the variability of climate parameters on the growth and production of yams (Adifon et al., 2020). The methodological approach he used is described in Table 9.

Table 9. Summary of the approaches to climate change on yam production

Data description/sources	Methods/Approaches/Period of the study	Country/Area/ References
Data are from secondary sources: - Yam area cultivated; - Climate data: CRU, ECMWF, ERA-Interim; - Validation data: station-based observations; - Historic climate datasets (Daily data for 120 years); - Future climate data: RCP 4.5 and RCP 8.5.	- Surveys using multistage sampling and random techniques in the selection of communities. - Establishing empirical climate variability over time from 1900 to 2019 (118 years); - Analyze a historic climate data period (1901-2019) with thirty-year (30) subdivisions made to four (4) non-overlapping epochal climate periods; - Future climate data period (2020-2050); - Statistical methods: Probability Density Function (PDF), trend analysis and change points analysis for establishing climate variabilities over time.	Guinea/ Savannah and Agro-ecological zone of Nigeria/ (Adeleke Aturamu et al., 2021)
Data are from secondary sources: - Slope inclination and length, topographical information; - Regional climate model outputs (GCM ECHAM5 downscaled) with A1B scenario; - REMO model and the A1B scenario output of the GCM HADC3Q0 downscaled; - The RCMs SMHIRCA and HADRM3P with the A1B scenario output; - Regional soil database from the soil association map; - Regional cropland database with the EPIC crop growth simulation model.	- Comparison of EPIC output for baseline (1961-2000) and time horizon (2001-2050); - Combines the agro-ecosystem model EPIC with the hydrological model SWAT (Soil Water Assessment Tool); - Changes in temperature and precipitation and the response of soil types to these changes; - Subdivision of the catchment into agronomic response units of variable size which constitute the spatial simulation units (LUSAC = Land Use-Soil Association-Climate units); - The LUSAC represent an area with similar climate conditions, soil characteristics and a representative crop and soil management; - Yield of yam had been calculated within each LUSAC for the period of 40 years (1961-2000) and 50 years (2001-2050). - Validation of the model: A total of four climate scenarios based on A1B and B1 emission scenarios with different RCM output has been simulated: The baseline period with the simulated historical data (1961-2000) and the time horizon (2001-2050) under IPCC SERES A1B and B1 scenario conditions. The CO_2 concentration was set at 350 ppmv for the baseline simulations.	Savanna zone of West Africa/ Particularly in the Upper Ouémé basin/ (Srivastava et al., 2012)
Data are from primary sources: - Daily climate data: temperatures, precipitation, potential evapotranspiration, relative humidity and insolation collected from the METEO-Benin; - Field data (Survey); - Yam yield data.	- Daily climate data period (1981-2016); - Survey from 351 producers to collect their perceptions about climate variability on the yams production; - Descriptive statistics analysis of the field data; - Principal component analysis (PCA) to determine the local perceptions of the effect of climatic parameters on yam production; - Trend analyses, Lamb index calculations and the agro-climatic stress index (ASI) using the climate data to determine the climate variability; - Yam yields by zone were calculated based on data collected from farmers and the yam areas cultivated by year; - The econometric approach based on ordinary least squares (OLS) has been adopted in order to identify among the climatic parameters those that best explain the yield of fresh yam tubers.	Central and Northern Benin/ (Adifon et al., 2020)

In 2019, the World Bank Group conducted a study on "*CLIMATE-SMART AGRICULTURE INVESTMENT PLAN*" with the contribution of the Coat of Arms of Ivory Coast, Initiative for Adaptation of African Agriculture (Initiative AAA), International Center for Tropical Agriculture (CIAT), Climate Change, Agriculture and Food Security (CCAFS) which is provided an investment plan for climate-smart agriculture (CSA) in Côte d'Ivoire. Situation analysis indicates that climate change will impact the production of key agricultural products in the country, which will, in turn, impact each economic activity. Climate change will drastically alter what crops are suitable for a given place, reducing suitability across large areas but also creating pockets of increased suitability. Modeling using the International Model for Agricultural Commodity and Trade Policy Analysis (IMPACT) suggests that the landscape of economic incentives will change, offsetting the loss of ability for some crops while exacerbating it for others (World Bank Group, 2019). Concerning the yam cropping, their study shows that the percentage point difference in yield and area of production with different levels of climate change for yams will be reduced negatively in yield under Regional Climate Projection (RCP) respectively in 2030 and in 2050 (RCP4.5: -0.9%; -2.3% and RCP8.0: -1.0%; -2.4%) and increased in production in the same RCP for respectively 2030 and 2050 (RCP4.5: 0.2%; 0.5% and RCP8.0: 0.1%; 0.4%) (Table 10).

Table 10. Percentage point difference in yield and area of yam production with different levels of climate change in Côte d'Ivoire. **Source:** (World Bank Group, 2019)

	Difference in yield (SSP3)				**Difference in area of production (SSP3)**			
	RCP 4.5		**RCP 8.0**		**RCP 4.5**		**RCP 8.0**	
	2030	2050	2030	2050	2030	2050	2030	2050
Yams	-0.9	-2.3	-1.0	-2.4	0.2	0.5	0.1	0.4

Note. SSP = Shared Socioeconomic Pathways; RCP = Representative Concentration Pathway.

5. Conclusion and Outlooks

Documentary research is a task to be carried out before embarking on a practical study. It enables gathering information from original papers about the work to be carried out. The objective of this study was, therefore, to review the state of the art on the topic entitled: «Yam production-related agro-climatological risks and yam yield modeling in Côte d'Ivoire». Four official national platforms (Ministry of Agriculture and Rural Development (MINADER), National Center for Agricultural Research (CNRA), National Agency for Rural Development Support (ANADER), Airport, Aeronautical and Meteorological Exploitation and Development Company (SODEXAM)) and six scientific search engines were investigated in this study including Theses.fr, African Journal Online, Science Direct, Google Scholar, WorldCat and Semantic Scholar. None of the results from these ten (10) search platforms found a study on Côte d'Ivoire according to the search terms. On the other hand, eight (8) related works in this field were retained and investigated. These documents deal with the climatic impact on yam and yam yield modeling in West Africa and the French Antilles (Guadeloupe). Regarding climate impact on yam cropping, the authors note the low annual yam yield rate caused by rainfall uncertainties, heat waves and soil infertility. As far as modeling, is concerned, three (3) models are the most widely used. These are Approach for Land Use Sustainability (SALUS) model, the Environmental Policy Integrated Climate (EPIC) model and the Cropping Systems Simulation (CROPSYST) model. In addition to these models, artificial intelligence through machine learning models had been used by some authors for yield prediction for several crops including yams. These models, as good as they are, present uncertainties and limitations in modeling studies and climate change on yam production. Concerning the yield modeling-based machine learning tools, the proposed prediction models are generalizable to the West African region and support large-scale data sets which increase uncertainties and large estimates in the outputs. On the other side, the variability of crop yields and season length simulated by SALUS, EPIC and CROPSYST models are highly dependent on the uncertainty of crop parameters and model calibration. These models, therefore, use simple relationships to represent yam growth and production. The pattern and magnitude of relationships between crop parameters and model output in these studies were consistent with typical responses of crop physiological processes and to the environment. However, few modeling studies have taken into account the dynamic simulation of disease effects and the simulation of crop phenology at the same time. This could be an advantage and improve the accuracy of the model. By doing so, the calibrated model could be used to improve fertilizer management in yam production and will solve a major problem in this sector for the greater happiness of yam farmers. Finally, it should be noted that all the models and tools used in these studies have been developed for several crops, so using them need to be accurately calibrated. In the case of yam, a specific model must be set up to fight against all kinds of environmental impact, as it is the main food crop in Côte d'Ivoire, with a production of 7853083.92 tonnes in 2021, the second most important in West Africa, and one of the most widely grown crops in Africa with 73493225.79 tonnes in 2021 according to Food and Agriculture Organization of the United Nations statistics.

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Breeding Programs Against Coffee Leaf Rust in Brazil: A Review

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Abstract

Leaf rust caused by *Hemileia vastatrix* Berk & Br. is the main disease that attack coffee plants all over the world. The disease causes 35-50% of yield loss in average in Brazil. The disease is present in all the countries that cultivate coffee (*Coffea arabica* L. and *C. canephora* L.). Resistance of coffee to leaf rust is the main method of disease control. But the great variability of the pathogen makes it very difficult. In the world and in Brazil there are more than 50 and 16 races of the pathogen, respectively. In Brazil there are seven research institutions that have been working with breeding programs against coffee leaf rust. The main source of resistance to coffee leaf rust used by all the research institutions in Brazil came from 'Centro de Investigação das Ferrugens do Cafeeiro-CIFC' in Oeiras, Portugal. They are: Híbrido de Timor (HdT) CIFC 832-1 and HdT CIFC 832 and HdT CIFC 2570. Crosses were made at CIFC with a variety Caturra and Vila Sarchi and sent to Brazil, Colombia and some countries of Central America and Caribean. The countries that received the germplasm of CIFC back crossed them with varieties Catuai and Mundo Novo. Crossing HdT with Caturra originated the group Catimor and HdT with Vila Sarchi the group Sarchimor. Other source of resistance to leaf rust came from *Coffea canephora* crossed with *C. arabica* originating the cultivar Icatu. But the great majority of the resistant cultivar came from Catimor and Sarchimor. More than 50 coffee varieties have been launched with resistance to the leaf rust in the last 40 years in Brazil. But only few of them remain with vertical resistance to all the races of *H. vastatrix*. Horizontal resistance is more common on *C. canephora* var. *conilon* and *C. canephora* var. *robusta* than in *C. arabica.* This revision has the purpose to relate to the scientific comunity the breeding programs against coffee leaf rust in Brazil.

Keywords: *Coffea arabica* L., *Hemileia vastatrix*, Híbrido de Timor, *Coffea canephora* L., Catimor, Sarchimor, vertical resistance

1. Introduction

In nearly all parts of the world where Arabica coffee was cultivated, the plant was attacked and suffered from leaf rust caused by *Hemileia vastatrix* Berk & Br. The disease infect the leaves, causes die back of the branches and gradually kills the coffee tree. The disease was first appeared in Srilanka at the end of 1860 following Sumatra-Indonesia in 1876 and probably in Timor-Leste in 1880. As a consequence of this disease most of the Arabica coffee plantation in Indonesia were abandoned and, in many cases, substituted to Robusta coffee plantations. In Srilanka coffee plantation was substituted by tea due to leaf rust.

In the America's the disease was first discovered in Brazil in 1970; then leaf rust spreads to all Latin and Central America countries, Caribean, Mexico and recently to Hawaii. Coffee leaf rust caused an epidemic in Brazil in 1970, and still causes 30-50% yield loss (Zambolim, 2016). Genetic resistance is the main measure of coffee leaf rust control. But the main problem is to find genetic resistance source to the disease in the world due to the genetic variability of the fungus *H. vastatrix.* There are mor than 50 races identified of the pathogen in the world; in Brazil there are 16 races of *H. vastatrix* identified (Varzea et al., 2005; Zambolim et al., 2005; Zambolim & Caixeta, 2021). Hopefully the portuguese's scientist's, back in the decade of 1920, discovered the Hibrido de Timor (HDT) plant, in the island of Timor-east resistant to coffee leaf rust, which is now the main source of genetic resistance to the disease all over the world. In this revision it will be presented all the breeding programs against coffee leaf rust.

2. Importance of Hybrido de Timor for Coffee Breeding Against Leaf Rust

Coffee appears to have been introduced into Timor-east in the middle of the eighteenth century. The first coffee plantations in Timor-east were from the Arabica species, a variety of Typica. The highlands of Timor-east were a refugee for Arabica coffee plantations where the incidence of the disease was less severe than in lowland. To obtain a plant resistant to the disease is an obstacle because *Coffea canephora* var. *robusta*, which tolerates the disease has a number of chromosomes of 2n = 2x = 22 while the chromosome of *C. arabica* is 2n = 4x = 44. In fact, to develop a plant that is resistant to the disease it can only be done through the duplication of the number of chromosomes of *Coffea canephora* var. *robusta* or natural crosses between different chromosomes of these two species. The latter situation occurred in Timor-east, allowing the appearance of a new coffee plant called 'Hibrido de Timor' (HDT) which is resistant to *Hemileia vastatrix*. The original plant of HDT is unique in the world because it resulted from unexpected crosses (by nature) and the plant has an incalculable historical value. The natural hybridization of HDT was confirmed by the former Portuguese Agronomic Studies Overseas Mission (MEAU) in Timor-east. According to the MEAU, the segregation of phenotypes occurred in progenies of HDT were some are closer to *C. arabica* and others closer to *Coffea canephora* var. *robusta*. This led to the assumption that HDT exist as a result of natural crosses between *C. arabica* and *C. canephora* var. *robusta*, in which probably an unreduced gamete of Robusta had combined with a normal from Arabica. It is assumed that the existence of the populations of HDT had originated from an unique plant which was part of an initial plantation of *C. arabica*, variety of Typica established in 1917s or in 1927 in an altitude between 800 and 820 meters above sea level. The original plant is located in a coffee plantation located at Mata Nova, area of Malhui, suco Fatobessi, sub district Hatolia, Ermera district. In various observations made from 1962 to 1975 suggested that the HDT plant was resistant to *Hemileia vastatrix* Berk. & Br., while devastating attacks were observed in the surrounding plantation of *Coffea arabica*. The discovery of the HDT provided an impetus for the establishment of the Centro de Investigação das Ferrugens do Cafeeiro (CIFC). This centre established in 1955 in Portugal with the support from the governments of Portugal and USA. The involvement of the USA in this project was due to the fact that there was a fear of a possible outbreak of coffee leaf rust in coffee production areas of Central and South America that potentially led to an economic crisis in these states.

The HDT was proved to be immune to 23 physiologies races of *H. vastatrix* at that time and this was demonstrated by CIFC, on the possibility of immunity transmission to F1, when crossing with *Coffea arabica* L., a high yield variety.

Nowadays almost 95 per cent of rust resistant coffee varieties cultivated around the world were directly or indirectly resulted from the studies conducted by CIFC, based on the 'Hibrido de Timor'. The resistance manifested in HDT to *H. vastatrix* suggested that Timor-east coffee production become a determinant factor in the worldwide diffusion of the seeds of HDT. The diffusion of the seeds of HDT was begun in 1955, after its restricted utilization during 10 years by the firm property of the plantation where the original plant of the hybrid first appeared. The first seeds were sent to CIFC in 1955 and were used by the CIFC to establish clones and progenies of HDT. Following this, from 1960, the seeds of HDT were distributed to the experimental stations in coffee production countries such as India, Tanzania, Kenya, Angola, Brazil, Costa Rica and Colombia. The populations of HDT are, naturally marked with a clear heterogeneity regarding the morphologic appearance, although the higher size is a constant characteristic, resistance to the coffee rust easily checked in the plantations and confirmed by CIFC, seed uniformity and productivity.

The general characteristic of the descendants of the original plant is to have a phenotype of *C. arabica* L., being predominant the tetraploid forms with 44 chromosomes, presenting the product appreciable organoleptic qualities, remarkable chemical similarity with Arabic, in exports has been commercially treated as Arabica and marked resistance to *H. vastatrix*.

The original HDT has had a very important direct use value, both for Timor-east and for all Arabica coffee producing countries, because it allowed to obtaining coffee varieties (either pure HDT varieties or crossed) resistant to rust. These new varieties have increased the production of Arabica coffee and increasing producers' income. For all above reasons, all producing and consuming countries of Arabica coffee owe a debt of gratitude to the nature of Timor-east, as this nature managed to do a miracle cross between two species with different chromosomes; one with diploid and the other with tetraploid. The objective of this review is to report the evolution of the breeding program of coffee varieties, resistant to leaf rust, from the HDT and other coffee sources (*C. canephora*) in several research institutions in Brazil.

3. Breeding Program of the Instituto Agronomico de Campinas

The first coffee breeding program in Brazil began in the 1930s at the Instituto Agronomico de Campinas (IAC) by Dr. Alcides Carvalho. National and international coffee growers owe a lot to Dr. Carvalho, as he dedicated his entire life to the improvement of coffee in the country. Later, Drs. Luiz C. Fazuoli, Herculano P. Medina Filho, Oliveiro G. Filho and Wallace Gonçalves joined the team. In its beginning, the IAC breeding program was aimed at the selection of more productive, rustic, long-lived and good quality cultivars. Thus, the cultivars Bourbon Vermelho, Bourbon Amarelo and Mundo Novo were chronologically selected (Carvalho et al., 1952). At a later stage, dwarfism genes from the Caturra variety were transferred to the 'New World', giving rise to the cultivars Catuaí Vermelho and Catuaí Amarelo (Carvalho & Monaco, 1972). The innovation drastically changed the system of conducting and managing crops, allowing greater density and facilitating the harvesting of plants. In 1950, a study was initiated with the objective of transferring rust-resistant alleles of *Hemileia vastatrix* from the species *C. canephora*, diploid (2n = 2x = 22 chromosomes) to the species *C. arabica*, tetraploid (2n = 4x = 44 chromosomes). The chromosomes of the species *C. canephora* diploid were duplicated to be crossed with *C. arabica* tetraploide. As previously mentioned, the disease only became a problem in Brazil almost 20 years later, but at that time it was already feared that it would be introduced in the country and the damage it could cause. From the result of the cross between the cultivar 'Robusta' of *C. canephora* and the Bourbon Vermelho cultivar of *C. arabica*, crossbred in 1956 with coffee plants selected from the cultivar Mundo Novo of *C. arabica*, it was found that several of the combinations showed rust-resistant plants in tests carried out at the CIFC in Oeiras, Portugal. Selected coffee trees derived from the first backcross to 'Mundo Novo' were, in 1960, crossed again in Oeiras, Portugal. In 1960, selected coffee plants derived from the first backcross to 'Mundo Novo' were crossed again with plants of this cultivar. The set of populations resulting from these hybridizations, with two or three backcrosses to 'Mundo Novo', was given the generic name of 'Icatu'. The coffee plants selected in the various backcrossing cycles were sent to the CIFC, so that the selection could be carried out there for resistance to rust, because at that time the disease had not yet been introduced in Brazil. The hybrid combinations obtained by IAC were vigorous and productive, although in some progenies a high number of aneuploid plants was noted. The selected coffee plants were resistant to most physiological races of *H. vastatrix*. In this material it was obtained immune coffee plants to those with only a slight attack, in which pustules and sporulation were minimal, and others with more intense sporulation. The tall cultivars called Icatu Vermelho, Icatu Amarelo and Icatu Precoce were launched in 1992 and were characterized by incomplete resistance to *H. vastatrix*. From the end of the 1970s, this vast selection program had the important support of the Food and Agriculture Organization of the United Nations (FAO) and began to count on the fundamental participation of Albertus Eskes, Jaap Hoogstraten and Masako Toma-Braghini. Coffee rust had not yet been detected in Brazil, which occurred only in 1970. Already anticipating the problem, the IAC, in the early 1950s, introduced a valuable and diverse collection of accessions from the United States Department of Agriculture (USDA), encompassing exotic varieties from various countries and diverse germplasm of Arabica coffee carriers S_H1 to S_H4 genes of resistance to the pathogen. Numerous hybridizations were carried out with the introduced germplasm and the cultivars from Brazil existing at the time. With this strategy, in the early 1970s, the IAC distributed to producers the cultivars Iarana-C 73 and Iarana-C 74 consisting of mechanical mixtures of coffee seeds with individual alleles S_H1, S_H2, S_H3 and S_H4 (Carvalho et al., 1975). In support of this vast programme, from 1956 onwards, a fruitful exchange of information on the genetic resistance of the coffee plant to *Hemileia vastatrix* Berk & Br began between the IAC and the Centro Internacional das Ferrugens do Cafeeiro (CIFC), in Oeiras, Portugal. At that time, the CIFC sent to the IAC a new collection of coffee accessions, to be tested in relation to their adaptation and productivity (Bettencourt & Carvalho, 1968). From the material received in 1971, several selections of coffee known as Hybrido de Timor (HdT) stood out, as well as descendants of hybridizations carried out in Portugal, between (HdT) and other sources of resistance to rust, such as a series of differentiating coffee trees for the races of *H. vastatrix*, known at the time (Bettencourt & Fazuoli, 2008). The HdT is the result of a natural cross between *Coffea arabica* and *C. canephora*; its selections, especially those with CIFC prefixes 832/1 and 832/2, showed resistance to the races of *H. vastatrix* known at that time and easily interbreed with cultivars of *C. arabica*.

The valuable germplasm forwarded by the CIFC was used in various hybridizations by the IAC (Bettencourt & Fazuoli, 2008) and gave rise to the cultivars Obatã IAC 1669-20, Tupi IAC 1669-33, both released in the year 2000 and IAC 125 RN and IAC Obatã 4739, registered in the National Registry of Cultivars of the Ministry of Agriculture and Supply (RNC/MAPA) in 2012. Although new races of *H. vastatrix* have broken the resistance of the cultivars Obatã IAC 1669-20 and Tupi IAC 1669-33, the cultivars IAC 125 RN and IAC RN e IAC Obatã 4739 are still resistant to all races of *H. vastatrix* identified in Brazil.

Finally, in 2016, IAC launched the IAC Catuaí S_H3 cultivar, with vertical resistance to coffee leaf rust. The cultivar comes from the introgression of the S_H3 gene of *C. liberica*, present in the BA 10 accession, from India, used in hybridizations with the cultivar Catuaí Vermelho IAC 46 (Fazuoli et al., 2019). In addition to being resistant to all races of the fungus identified in Brazil so far, the cultivar has a good level of tolerance to water deficit.

The following rust-resistant materials, released by the Instituto Agronômico de Campinas, are on Table 1.

According to the Table 1 there are four varieties with vertial or quantitative resistance to coffee leaf rust. The others present horizontal or quantitative resistance.

Table 1. Coffee lines released by the Instituto Agronômico de Campinas (IAC)

Rust-resistant tall cultivars		
Icatu Vermelho	Initial cross between *C. canephora* DP and Bourbon Vermelho, with two backcrosses to 'Mundo Novo', released by the IAC in 1992.	Moderately susceptible
Icatu Amarelo	Initial cross between 'Icatu Vermelho' and 'Bourbon Amarelo' or 'Mundo Novo Amarelo' released by the IAC in 1992.	Moderately susceptible
Icatu Precoce IAC 3282	Initial cross between 'Icatu Vermelho' and 'Bourbon Amarelo', selected and released by the IAC in 1996.	Moderately susceptible
Rust-resistant undersized cultivars		
Obatã IAC 1669-20	Initial cross between 'Villa Sarchí' and the Híbrido de Timor CIFC 832/2, with natural backcrossing to 'Catuaí Vermelho', was released by the IAC in 2000.	Moderately resistant
Tupi IAC 1669-33.	Initial cross between Híbrido de Timor CIFC 832/2 and Villa Sarchí (H361-4) carried out by CIFC, having been selected and released by IAC in 2000.	Resistant
IAC Obatã 4739	The cultivar IAC Obatã 4739 is derived from the cross between the coffee plant IAC 1669-20-1 and the cultivar Catuaí Amarelo IAC 62.	Resistant
IAC 125 RN	Initial cross between Híbrido de Timor CIFC 832/2 and Villa Sarchí carried out at CIFC (H 361-4), with subsequent selection by IAC	Resistant to leaf rust and to races 1 and 2 of *Meloidogyne exigua* (Fazuoli et al., 2018) and races 1 and 3 of *M. incognita* (Fazuoli et al., 2018).
IAC Catuaí SH3	IAC Catuaí SH3 was obtained by the genealogical method, from the recombination between the coffee plant H 2077-2-5-46, from the Catuaí Vermelho germplasm and the accession IAC 1110-8, from the exotic cultivar BA10. The cultivar IAC Catuaí SH3 (Fazuoli et al., 2019).	Resistant

4. Breeding Program to Leaf Rust of the Universidade Federal de Viçosa (UFV)

The Coffee Breeding Program began at the Universidade Federal de Viçosa (UFV) shortly after the coffee rust was found in Bahia, Brazil in 1970. The professors who started the improvement program were Geraldo Martins Chaves and João da Cruz Filho. Later Professor Laércio Zambolim and Dr. Antonio Alves Pereira from the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig) was incorporated in Program.

The Coffee Germplasm Bank of the UFV, located in Viçosa, State of Minas Gerais, was created in 1970/71, initially with about 450 accessions, containing great genetic variability including sources of resistance to *Hemileia vastatrix* and *Meloidogyne exigua*. These introductions came from the Coffee Rust Research Centre (Centro de Investigação das Ferrugens do Cafeeiro, CIFC), Portugal, the National Coffee Research Centre (CENICAFÉ), Colombia, the Inter-American Institute of Agricultural Sciences (IICA), Costa Rica and the Agronomic Institute of Campinas (IAC), Brazil, and were planted at the Fundão Experimental Station at the Universidade Federal de Viçosa. After the arrival of the coffee germplasm, resistant to coffee leaf rust derived from Catimor (Caturra vermelho × CIFC Híbrido de Timor 832-1) and Sarchimor (Villa Sarchi × CIFC Híbrido de Timor 832-2) from CIFC in the F1, F2, F3, the advancement of generations and backcrosses with agronomically adapted varieties of *C. arabica* began (Catuaí Vermelho and Mundo Novo).

Accessions of the germplasm were also sent to other Brazilian research (Epamig, Procafé and Incaper) and to coffee farmers to be studied in different regions of the country. In 2006, 1,036 accessions were incorporated to the germplasm bank. The new accessions were planted at the Experimental Station located near the Airport at the Universidade Federal de Viçosa. This germplasm included 200 new accessions of *Coffea arabica* of the varieties Bourbon Vermelho, Bourbon Amarelo, Sumatra, San Ramon, Caturra, Botucatu Amarelo, Laurina, São Bernardo, Típica, Pacas, Vila Lobos, Geisha and others. Several accessions of Híbrido de Timor, their derivatives (Catimor, Sarchimor, Cachimor and Cavimor) and Catindu were also planted in this location, to preserve this importante genetic variability. Numerous materials from Central America (Costa Rica and Turrialba) were also incorporated into the program.

The first variety launched as leaf rust resistant by UFV was named Oeiras, in honor of the city of Oeiras, Portugal where the Coffee Rust Research Center (CIFC) is located. This variety is also drought tolerant. From then on, the UFV Germplasm Bank was used in several coffee genetic improvement in Brazil, enabling the development of new cultivars such as Paraíso MG H419-1, MGS Paraíso 2, Catiguá MG1, Catiguá MG2, MGS Catiguá 3, MGS Ametista, MGS Aranãs, MGS Turmalina, Sacramento MG1, Pau-Brasil MG1, Araponga MG1, Sarchimor MG8840, among others in partnership with Dr. Antônio Alves Pereira from Epamig and Dr. Antônio Carlos Baião de Oliveira from Embrapa (Table 2).

From the year 2000, Professor Laércio Zambolim stablished a collection of Híbrido de Timor, at the Universidade Federal de Viçosa and, today the germplasm has 156 accessions, cultivated at the experimental center of Fundão (UFV). All clones were characterized by molecular markers and resistance to races $II_{\mathbf{v5}}$ and $XXXIII_{v5,7,9}$ of *H. vastatrix.* There is no known collection of Híbrido de Timor in the world that contains this large number of accesses.

The best accessions of Híbrido de Timor resistant to leaf rust were crossed and backcrossed with *C. arabica* to develop new varieties. In view of the valuable coffee germplasm, from the cross between the Caturra variety with the Híbrido de Timor (Catimor) and the Villa Sarchi variety with the Híbrido de Timor (Sarchimor) existing at UFV the coffee biotechnology program was initiated at UFV in cooperation with Embrapa. The coffee biotechnology program was initiated by Dr. Eveline Teixeira Caixeta (Embrapa) and Professors Ney Sussumu Sakiyama and Laércio Zambolim (UFV) at the UFV. From 2003, molecular technologies, such as molecular markers and genomics, has been applied in germplasm conservation, in genetic breeding, in genealogy analysis and in the cultivar identification. The molecular tools allowed development and availability of different molecular markers, as well as, cloning and characterization of genes involved in rust resistance. Besides, genomic data on coffee plants and their pathogens has been available to provide opportunities for large-scale discovery of new targets for disease control. All these tolls have allowed the integration of phenotypic and genotypic data for selection of superior and rust resistant coffee genotypes. Thus, molecular approaches are being applied in the coffee breeding program to assist in the parent selection, superior genotypes assisted selection and increase the efficiency of the new cultivar development. The potential of the applied molecular methodologies lies not only in the time reduction of the program, but also in the solid scientific basis that can explain the genetics and biochemistry of the changes that have occurred or that may occur in the genetic breeding process.

Table 2 shows that five varieties had vertical and three had horizontal resistance to *H. vastatrix*, respectively to race $XXXIII_{v5,7,9}$. A hundred per cent of the varieties came from the group of coffee denominated Catimor.

Table 2. Coffee germplasm released by the Universidade Federal de Viçosa in cooperation with the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais with vertical and horizontal resistance to *H. vastatrix* race $XXXIII_{v5,7,9}$

Germplasm	Crossing	Type of resistance to race $XXXIII_{v5,7,9}$
Oeiras	Caturra vermelho (CIFC 19/1) × Hibrido de Timor (CIFC 832/1)	Horizontal or quantitative
Paraíso MG H419-1	Catuaí amarelo IAC 30 × Híbrido de Timor 445-46	Vertical or qualitative
Catiguá MG-1	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Catiguá MG-2	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Catiguá MG 3	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Sacramento MG-1	Catuaí vermelho IAC 81 × Híbrido de Timor 438-52	Horizontal or quantitative
Pau-Brasil MG-1	Catuaí vermelho IAC 141 × Híbrido de Timor 442-34	Vertical or qualitative
Araponga MG-1	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 446-08	Horizontal or quantitative

5. Genetic Improvement Aimed at Rust Resistance at the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná)

The coffee breeding program of the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná) began its research on genetic improvement for rust resistance with Dr. Tumoru Sera in 1975. In the year 2012 Dr. Gustavo H. Sera joined the group of researchers. The main breeding method used by IDR-Paraná was genealogical and *bulk* and backcrosses were used in some cases. The sources of resistance most used by the IDR-Paraná breeding program were coffee plants derived from: Híbrido de Timor (HdT), Sarchimor, Catimor, Icatu, BA-10, wild accessions from Ethiopia and landraces. HdT, Sarchimor, Catimor and Icatu are Arabica coffee plants carry *C. canephora* genes, while BA-10 is an Arabica coffee plant that carries *C. liberica* genes. Ethiopia's wild accesses and landraces (*e.g.*, Geisha, Rume Sudan, Java, etc.) are pure Arabica coffee trees. The main coffee germoplasm employed by IDR-Paraná were HdT CIFC 832/1, HdT CIFC 832/2 and HdT CIFC 2570. The HdT CIFC 832/2 were the most used germplasm in genetic improvement and, currently, several progenies of HdT CIFC 2570 are also being used as sources of resistance to *H. vastatrix*. These sources of resistance have major genes that promote qualitative resistance to leaf rust pathogen. Quantitative-type resistance is expressed when major genes are broken down by new rust races (Sera et al., 2022a). In general, some varieties derived from HdT as well as all coffee plants with S_H3 gene, still maintain high level of resistance to rust in Brazil. On the other hand, the qualitative resistance has already been broken in coffee plants derived from Icatu, wild accessions of Ethiopia and *landraces*, and currently have intermediate level of resistance. Fiftheen cultivars resistant to coffee leaf rust were released by the IDR-Paraná (Sera et al., 2022b). The Coffee germoplasm released by the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná) are on the Table 3.

Table 3 shows that six varieties had vertical and nine horizontal resistance to *H. vastatrix*, respectively. IAPAR 59, IPR 97, IPR 98, IPR 104, IPR 107 and IPR Pérola have qualitative resistance genes (major SH genes) that have not yet been broken by physiological rust races present in the field in Brazil. IPR 101 and IPR 105 are carriers of the major S_H3 gene and for this reason are also highly resistant to rust. Although IPR 100 is a derivative of BA-10 coffee, this cultivar is susceptible to leaf rust because it is not carry the gene S_H3.

The resistance of the cultivars IPR 99, IPR 102 and IPR Alvorada was broken in some places in Brazil, while the resistance of IPR 103, IPR 106 and IPR 108 has already been broken in most coffee regions of the country. These six cultivars have intermediate level of resistance due to the action of minor genes. Currently, IDR-Paraná is developing cultivars with high resistance to rust from the combination of the genes S_H3, S_H5, S_H6, S_H7, S_H8, S_H9, $S_H?$, originated from the coffee plants Sarchimor and BA-10, aiming at durable qualitative resistance. Selection assisted by molecular markers associated with S_H3 has been routinely adopted in the IDR-Paraná. In order to increase the amount of minor resistance genes, with a consequent increase in the intermediate resistance level. Several progenies were developed from crosses between the Sarchimor, Icatu, Ethiopian wild accessions and landraces.

Table 3. Coffee germplasm released by the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná)

Germplasm	Crossing	Type of resistance
IAPAR 59, IPR 97, IPR 98, IPR 104	Sarchimor group: Villa Sarchi CIFC 971/10 × HdT CIFC 832/2	Vertical or qualitative
IPR 101, IPR 105	Catuai Vermelho × (Catuaí × BA-10)	High horizontal or quantitative
IPR 100	Catuai Vermelho × (Catuaí × BA-10)	Low horizontal or quantitative
IPR 106	Spontaneous cross between Icatu IAC 925 × Unknown coffee	Horizontal or quantitative
IPR Alvorada	IAPAR 59 × Mundo Novo IAC 376-4	Horizontal or quantitative
IPR 107, IPR Perola	IAPAR 59 × Mundo Novo IAC 376-4	Vertical or qualitative
IPR 108	IAPAR 59 × (Icatu anão × Catuaí)	Horizontal or quantit.
IPR 102, IPR 103	Icatu Anão × Catuaí Vermelho	Horizontal or quantitative
IPR 99	C. arábica 'Villa Sarchi' CIFC 971/10 × 'Hibrido e Timor' CIFC 832/2	Horizontal or quantitative

6. Genetic Improvement Program Against Coffee Leaf Rust Developed by Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig)

The use of genetic resistance of coffee plants to *Hemileia vastatrix* Berk. & Br. was the main long-term goal for controlling leaf rust. In the State of Minas Gerais, research began at the Universidade Federal de Viçosa (UFV) and later the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig) joined the program. Since 1971/72, in a close partnership with UFV, Epamig developed an intense and aggressive research program aimed at genetic control of leaf rust as well as other diseases such root-knot nematodes. Breeding research, aiming to obtain rust-resistant cultivars, was initiated in 1970/71 by the Departamento de Fitopatologia (DFP) da UFV, Minas Gerais, Brazil, under the leadership of Professor Geraldo M. Chaves and Professors. João da Cruz Filho and Laércio Zambolim with the introduction of a vast and valuable coffee germplasm carrying genes of resistance to *H. vastatrix* from the Centro de Investigação das Ferrugens do Cafeeiro-CIFC, Oeiras, Portugal and from the National Centre for Coffee Research-CENICAFÉ, Chinchina, Colômbia, the Inter-American Institute for Cooperation on Agriculture (IICA), Turrialba, Costa Rica, and the Instituto Agronômico de Campinas (IAC), Campinas, Brazil. The introduced material initially totaled about 450 accessions, including sources of resistance to coffee leaf rust. The introduced germplasm was tested for resistance to *H. vastratrix* at the DFP of UFV using mixture of uredospores harvested in the field. The resistant plants were planted in an experimental area of DFP/UFV, to constitute the *Coffea* spp. germplasm bank, to be used in the Coffee Genetic Improvement Program developed by UFV, in partnership with Epamig. Thus, this program was developed according to the following scheme: evaluation and selection of the introduced germplasm and synthesis of new genetic combinations of rust-resistant coffee plants. The new commercial coffee cultivars resistant plants obtained were planted in an experimental area of DFP/UFV, to constitute the *Coffea* spp. Germplasm Bank, to be used in the Coffee Genetic Improvement Program developed by UFV, in partnership with Epamig.

From 2005, Epamig started the implementation of a germplasm bank (BAG) of *Coffea* spp. in the Experimental Field of Patrocínio-CEPC. The CEPC is geographically located in the Alto Paranaíba region of the State of Minas Gerais, at an approximate altitude of 950 to 1,000 meters, latitude of 19°57′09″S and longitude of 46°28′12″W, with an average annual temperature of 20.7 °C, an average maximum annual temperature of 27.9 °C and an average minimum annual temperature of 14.8 °C. In this bank, a vast germplasm of *Coffea* spp. is being preserved, consisting mainly of most of the commercial cultivars, older cultivars as well as selections of HdT existing in Brazil and promising progenies of the various populations generically called Catimor, Sarchimor, Cavimor, Cachimor, Catindu and other selections bearing the rust resistance factors S_H1 to S_H10. In addition to this, the bank has accessions of other species of the genus Coffea, such as *C. canephora*, *C. racemosa*, *C. liberica*, *C. stenophylla*, among others. The collection currently consists of 1626 accessions from the Universidade Federal de Viçosa, private properties located in the states of Minas Gerais, São Paulo, Paraná and Espírito Santo, Experimental Research Center Café Elói Carlos Heringer, in Martins Soares-MG, of the Experimental Center Pioneers of Coffee of the Cerrado, in Patrocínio, of the Instituto Agronomico de Campinas, Campinas-SP, Experimental Field of Machado (CEMA/EPAMIG) and of the IDR-Paraná. Epamig has six Experimental Fields located in the municipalities of Patrocínio, Machado, São Sebastião do Paraíso, Três Pontas, Oratórios and Leopoldina, in the state of Minas Gerais. In these Fields and in private properties breeding research program is carried out aiming at resistance to leaf rust and other agronomic characteristics. In addition to rust, several accessions of the Epamig germplasm bank are carriers of genes for resistance to nematodes, fungal and bacterioses that attack the coffee plants (Nadaleti et al., 2022; Fassio et al., 2020). Several cultivars have already been registered and launched for commercial plantations in the state of Minas Gerais and in other states. Some of these cultivars are even being planted in other countries, located in Central America and the Caribbean and in other parts of the world. The cultivars with resistance to rust and/or nematodes developed by the program so far are on the Table 4 (Botelho et al., 2022; Salgado et al., 2022).

Table 4 shows that four of the varieties have vertical and one horizontal resistance to *H. vastatrix*, respectively. All the vertical resistance varieties came from the resistance source Catimor (CIFC 832/1).

Table 4. Cultivars with resistance to rust and/or nematodes developed by the Empresa de Pesquisa do Estado de Minas Gerais (Epamig)

Cultivar	Crossing	Type of Resistance to *H. vastatrix*
MGS Aranãs	Catimor UFV 1603-215 × Icatu IAC H3851-2	Vertical or qualitative
MGS Ametista	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 446-08	Vertical or qualitative
MGS Paraíso 2	Catuaí Amarelo IAC 30 × Híbrido de Timor UFV 445-46	Vertical or qualitative
Sarchimor MG 8840	Villa Sarchi (CIFC 971/10) × Híbrido de Timor CIFC 832/2)	Vertical or qualitative
MGS Catucaí Pioneira	Icatu × Catuaí	Horizontal or quantitative
MGS Vereda	Catuaí Vermelho × Amphillo MR 2-161	*Meloidogyne paranaenses*
MGS Guaiçara	Catuaí Vermelho × Amphillo MR 2-474	*Meloidogyne paranaenses*

7. Genetic Improvement Program Against Coffee Leaf Rust Developed by the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (Incaper)

The species *Coffea canephora* has great economic and social importance in the State of Espírito Santo, the second largest coffee producer in the country and the largest national producer of the species. In addition, it is currently a basic genetic material in Brazil for studies of resistance to rust and nematodes, mechanisms that determine drought tolerance, among others. The species *C. canephora* var. *conilon* and *C. canephora* var. *robusta* have been cultivated in Brazil, but in state of Espirito Santo only *C. canephora* var. *conilon*. The introduction of this coffee specie in the state until the 90's occurred through the sexual multiplication of mother plants selected by the farmers themselves, over the years. This provided the establishment of populations with wide genetic variability. The performance of Conilon crop in the state has shown great evolution in the last 20 years, due to the technologies that were developed by Incaper such as: genetic improvement, management of programmed cycle pruning, nutrition, irrigation, among others. The genetic improvement program initiated in 1985, using as an initial strategy the selection of plants with desirable phenotypic characteristics in several municipalities in the northern region of the state, cloning of the selected plants and evaluation of them in clone competition trials in the Incaper experimental station. Based on the experimental results and genetic compatibility tests, four clonal varieties and one seminal variety (Emcapa 8111, Emcapa 8121, Emcapa 8131, Emcapa 8141-Robustão Capixaba) and one for seed propagation (Emcaper 8151-Robusta Tropical) was released (Table 5). In the late 1990s until 2020, Incaper released the following varieties of *C. canephora* var. *conilon*: variety Vitória Incaper 8142 (formed by thirteen clones); Variety Marilândia (formed by 12 clones); Diamante variety (formed by nine clones); Jequitibá variety (formed by nine clones) and Centenária variety (formed by eight clones) (Table 5). In 2017, another seminal variety, the Conquista Incaper 8152 was released (Table 5). The Active Bank of Coffee Germplasm of the Incaper, located at the Marilândia Experimental Station has the purpose of conservation and evaluation of the superior genetic material of *C. canephora* with 576 accessions, with 10 plants/accession. These materials representatives of the Conilon or Kouilou group of *C. canephora* were selected from crops in different municipalities in the north of the states of Espírito Santo, Minas Gerais, Bahia, Rondônia and São Paulo (IAC). The genetic improvement program started with Dr. Romário G. Ferrão and then the program had the inclusion of Dr. Maria A. G. Ferrão and Dr. Aimbiré Fonseca. Later, Dr. Abraão C. Verdin Filho and Paulo C. Volpi joined the team. The species *C. canephora* is native to the lowlands of the equatorial region of Africa, located in the areas from Guinea to Uganda, Central.africa and especially Congo. There are two low collections with the genus diploid Coffea. The first is maintained in Madagascar and the second in Ivory Coast, for coffees originating on the African continent. The accessions conserved in the Incaper germplasm bank have been characterized primarily through the evaluation of morphological traits, based on descriptors defined a priori for the species and of direct interest to growers. However other complementary characterization techniques have been used, such as molecular and biochemical. There is a great concern about the maintenance of the genetic materials, since the use of clonal varieties provides a significant reduction in the diversity of the cultivated material. The introduction of the germplasm from Guinea, Uganda and Angola was done once. For this reason, the genetic basis of existing populations is considered to be narrow. More divergent germplasm from these countries should be introduced in the state. The increase in genetic variability was done through the introduction of materials from other institutions, such as the 26 new genotypes of the species *Coffea canephora* belonging to genetic groups distinct from conilon in October 2003 and 65 new genotypes of *Coffea canephora* belonging to distinct genetic groups of Conilon from the Instituto Agronômico de Campinas. The great majority belongs to distint groups of Conilon from Universidade Federal de Viçosa. These materials, added to eight other genotypes characteristic of the genetic group known as "robusta" and rescued in the state itself, were introduced into the Germplasm Bank in order to know their behavior in all the coffee regions, as well as to provide conditions for the identification of characteristics of interest that can later be transferred to materials with agronomic and commercial characteristics already known.

Seven clonal varieties and two propagated by seeds presented horizontal resistance to *H. vastatrix* under field conditons (Table 5). But observations of the clones of the varieties cultivated in several regions of the Espirito Santo state showed that some of them presented vertical resistance. Each clones of the varieties is planted in rows.

Table 5. Cultivars with resistance to leaf rust developed by the Instituto Capixaba de Pesquisa e Extensão Rural do Estado do Espírito Santo (Incaper)

Cultivar	Number of clones used in the formation of the cultivar	Type of Resistance to *H. vastatrix*
Emcapa 8111	9	Horizontal or quantitative
Emcapa 8121	14	Horizontal or quantitative
Emcapa 8131	9	Horizontal or quantitative
Emcapa 8141-Robustão Capixaba	10	Horizontal or quantitative
Emcaper 8151-Robusta Tropical (seed propagation)	Open pollination of 53 elite clones	Horizontal or quantitative
Vitória Incaper 8142	13	Horizontal or quantitative
Diamante ES 8112, ES 8122	9	Horizontal or quantitative
Jequitibá	9	Horizontal or quantitative
Centenária ES 8132	8	Horizontal or quantitative
Conquista	Propagation via seeds	Horizontal or quantitative

8. Genetic Improvement Program Against Coffee Leaf Rust Developed by the Fundação de Apoio Tecnológico à Cafeicultura (Fundação Procafé)

The agronomists who initiated the Procafé program were: José B. Matiello, Saulo R. de Almeida, Roque A. Ferreira and Maurício A. Bento. Sometime later, the following agronomists joined the team Dr. Carlos H. S. de Carvalho. Most of the germplasm bank is maintained at the 'Estação Experimental de Varginha, State of Minas Gerais (FEV). This experimental farm was set up in 1976. Genetic materials selected for the breeding program were also evaluated in different locations in the states of Minas Gerais, São Paulo, Espírito Santo and Bahia. In these states, partnerships were established with coffee growera. Currently, the Foundation has a germplasm bank with about 600 accessions, most of which are genetic materials from *Coffea arabica* with different degrees of inbreeding, and part of these materials is used in genetic improvement. In this database, it is possible to find accessions of cultivars that participated in the history of coffee culture in Brazil, as well as accessions of great importance as a source of agronomic interest, such as drought tolerance, resistance to pests, diseases and nematodes, special beverage and seed size. The breeding program developed by the Ministério da Agricultura /Foundation released for commercial planting are: Acauã, Acauã Novo, Arara, Azulão, Catucaí 785-15, Catucaí Amarelo 785-15, Catucaí Amarelo 2015479, Catucaí Amarelo 2SL, IBC-Palma-1, IBC-Palma-2, Japy, Sabiá Tardio and Saíra resistant to leaf rust (Table 5) (Carvalho et al., 2022; Sera et al., 2022a). The program also works with the development of cultivars with resistance to the leaf miner: cultivars Siriema AS1 (seed propagation), and clonal cultivar Siriema VC4 (Table 6) (Carvalho et al., 2022). Two varieties had vertical resistance to *H. vastatrix*; the great majority had horizontal resistance. The group of coffee plants that originated most of the resistant varieties was Sarchimor (CIFC 832/2). Thirteen varieties originated from Sarchimor and four from Catimor (Table 6).

Table 6. Most importante commercial varieties resistant to leaf rust released by the Fundação Procafé

Variety	Crossing	Type of resistance
Acauã	Mundo Novo IAC 388-17 × Sarchimor IAC 1668	Vertical or qualitative
Acauãma	Catucaí amrelo × Acauã (natural crossing)	Horizontal or quantitative
Acauã Novo	Sarchimor 1668 × Mundo Novo	Vertical or qualitative
Arara	Catuaí amarelo × Obatã (natural crossing)	High horizontal or quantitative
Azulão (Catucaí vermelho 36/6-366	Catuaí vermelho × Icatu vermelho 785	High horizontal or quantitative
Catucaí vermelho 36/6-366	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí 785-15	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 06/30	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 24/137	Catuaí vermelho × Icatu vermelho 785	Very low horizontal or quantitative resistance
Catucaí Amarelo 20/15-479	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 20/15-476	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 2SL	Catuaí× Icatú (natural crossing|)	Horizontal or quantitative
IBC-Palma-1, Palma 2	Catuaí vermelho IAC 82 × Catimor UFV 353	Horizontal or quantitative
Japy	Selection of Catucaí vermelho 19/8	Horizontal or quantitative
Sabiá Tardio	Acaia × Catimor UFV 386	Horizontal or quantitative
Saíra	Catuaí amarelo IAC 86 × Catindú (UFV 374 cv 643)	Horizontal or quantitative
Siriema 842	*Coffea arabica* × *C. racemosa* Crossed again with Catimor UFV 417	Horizontal or quantitative High resistance to leaf minor

9. Genetic Improvement Against Coffee Leaf Rust in Embrapa Rondônia

In July 1975, the Unidade de Execução de Pesquisa de Âmbito de Territorial (UEPAT), Porto Velho, RO) was created. Through partnerships and demands from the newly settled settlers, pioneering experiments in agronomic evaluations of cultivars and lines of Arabica coffee trees were implemented in selected rural plots (IAC Mundo Novo). At the beginning of the colonization the technicians detected a focus of the leaf rust fungus. Soon the disease disseminated in the emerging coffee-producing regions, attacking coffee plants of the cultivars of *C. arabica* L. (cv. Mundo Novo) and *C. canephora* Pierre ex. Froehner (Conilon botanical variety of unknown genetic origin). The epidemiological cycle was estimated and temporal spraying programs were determined for the chemical control of leaf rust currently the main foliar disease in coffee plants in Rondônia. Since this time, leaf rust has been considered the main key disease of coffee plants in the Northwest (Mato Grosso and Rondônia, States), causing direct damage to young and adult plants due to intense defoliation and reduction in coffee bean yield. Significant decreases in grain production had been observed, reaching up to 40% (compared to control treatment), under environmental conditions favorable to leaf rust (Veneziano et al., 1983). The results of the epidemiological studies showed that *H. vastatrix* initiated in December-January and increased the severity until March-April. Then, in the dry season, the disease progressively declined until August, stabilizing at a low rate until October.

In the epidemiological cycle of *C. arabica* rust, determined in the Aw environment of the village of Cacoal-Rondonia, it was noted that the evolution of the disease would occur in the period between September to November.

After 20 years, the technological reality of the state's coffee growing has changed markedly. Coffee cultivation based on the production of arabica ceased to exist due to economic unfeasibility and correlated factors. Farmers mostly started to explore technified clonal coffee cultivation based on conilon. At Embrapa Rondônia, since 2000, the focus on the medium-long term genetic improvement program with the coffee species *Coffea canephora* Pierre ex. Froehner has been the selection of plants with high productive potential, structural architecture compatible with dense planting, uniform fruit maturation cycle, superior quality of the beverage. In addition to environmental sustainability and the damage the disease cause to coffee production, the phytosanitary selection criteria adopted prioritized genetic resistance (total or partial) to the main diseases of coffee cultivation in the Western Amazon Region caused by fungal pathogens, especially leaf rust (*H. vastatrix* Berk & Br.) and brown spot (*Cercospora coffeicola* Berk. & Cook) and root-knot nematodes (Meloidogyne spp.). In order to achieve the objectives proposed by the program for the genetic improvement of coffees (*C. canephora* and *C. arabica*) of Embrapa Rondônia, the potential genetic variability was mantained in the Active Germplasm Bank (BAG-Cafés), at the Experimental Station of Ouro Preto do Oeste (10°43′44.51″S; 62°15′09.78″W; 249 m; clia Aw) and central-eastern region of Rondônia. BAG-Café (*C. arabica*) was installed in 1982 with 50 accessions (commercial cultivars and unregistered lineages). Due to the lack of demand for Arabica coffee due to the climate conditions, researchers deactivated the program. BAG-Cafés (*C. canephora*) in Rondonia was installed in 1988. The number of active accessions (seminal and clonal) of the two botanical *C. canephora* var. *robusta* and *C. canephora* var *conilon* fluctuates over time. A total of 450 accessions of *C. canephora* var. *robusta* (R) and *conilon* (C) and spontaneous intervarietal hybrids [R×C]) are maintained and characterized by phenotypic, genetic descriptors and biochemical response to leaf rust and root-knot nematode as well as quality of the beverate (Fonseca et al., 2022).

Currently, 30% of the clonal accessions are of conilon from spontaneous hybrids pre-selected from among 780 clones collected in commercial coffee plantations in several municipalities in Rondônia, during the three prospecting expeditions carried out in the years 1985 to 1988. As a result of the field collections a multiclonal cultivar Conilon 'BRS Ouro Preto', formed by the grouping of 15 superior clones (Ramalho, et al., 2016). Was released for the growers The BRS cultivar Ouro Preto was registered (RNC/MAPA Nº 29486 on 04/05/2012) and protected (Nº 20130061 as of 10/09/2012) at the National Service for the Protection of Plant Varieties-SNPC/MAPA. The phytosanitary criteria of selection and characterization adopted for clones of 'Conilon' prioritized resistance or tolerance to the main diseases of the regional coffee plants: leaf rust (*H. vastatrix* Berk. et Br), brown eye spot (*Cercospora coffeicola* Berk. & Cook), leaf spot and blight (Colletotrichum spp.) and root-knot nematodes (*Meloidogyne exigua*).

Nowadays approximately 50% of clonal and seminal accessions are pure 'robustas' and intergroup hybrids. These accessions are the result of stratified mass selection in the progenies of robustas and seminal conilons from the IAC in 1983. These genotypes were evaluated in Rondônia during 10 harvests for resistance or high genetic tolerance to leaf rust and root-knot nematodes (Veneziano, 1993; Rocha et al., 2021).

10. Conclusions

(1) The main source of resistance to coffee leaf rust used by all the research institutions in Brazil came from 'Centro de Investigação das Ferrugens do Cafeeiro-CIFC' in Oeiras, Portugal. They are: Híbrido de Timor (HdT) CIFC 832-1 and HdT CIFC 832 and HdT CIFC 2570. Other source of resistance to leaf rust came from *Coffea canephora* crossed with *C. arabica* originating.

(2) *Coffee liberica* L. with the gene S_H3 is another source of resistance to leaf rust.

(3) The great majority of the resistant cultivar came from Catimor and Sarchimor. More than 50 coffee varieties have been launched with resistance to the leaf rust in the last 40 years in Brazil.

(4) The great majority of the varieties released by the research institutions in Brazil, with vertical resistance was broken after eight to ten years under field conditions.

(5) After the loss of vertical resistance in the field, the varieties presented different levels of horizontal resistance.

(6) The great varieties released with vertical resistance was from the group Sarchimor.

(7) Horizontal resistance is more common on *C. canephora* var. *conilon* and *C. canephora* var. *robusta* than in *C. arabica*.

(8) *Coffea canephora* var. *conilon* and *C. canephora* var. *robusta* shows more drought tolerance than *C. arabica* in the field.

(9) The great variability of *H. vastatrix* affects the durability of the coffee cultivars in the field. No Brazil there are more than 16 races of the pathogen.

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Authors Contributions

Author Laércio Zambolim coordinated all the review and in the interpretation of the results of *Coffea arabica* and *Coffea canephora*. Eveline Teixeira Caixeta helped in the interpretation of the data. Oliveiro Guerreiro Filho collected the data of *Coffea arabica*. Gustavo Sera collected the data of *Coffea arabica*. Tumoro Sera collected the data of *Coffea arabica*. Antônio Alves Pereira collected the data of *Coffea arabica*. Antônio Carlos Baião de Oliveira collected the data of *Coffea arabica*. Abração Carlos Verdin Filho collected the data of *Coffea canephora*. Carlos Henrique de Carvalho collected the data of *Coffea arabica*. André Ramalho collected the data of *Coffea canephora*. All authors read and approved the final manuscript.

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