












Research Article

Genetic resistance of some potato (*Solanum tuberosum* L.) cultivars to late blight caused by *Phytophthora infestans* (Mont) de Bary under natural conditions

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Abstract

Late blight caused by the Oomycete *Phytophthora infestans* is the most destructive and dreaded disease for potato growers. Crop resistance development by selecting varieties with resistance traits is a promising approach for disease control. This study, aimed to determine the response of potato varieties to *Phytophthora infestans* infection under natural conditions. Twelve potato varieties were screened using a completely randomized Fisher block design with three replicates. Growth parameters, disease incidence, disease severity, and yield were assessed. The contents of selected biochemical resistance markers in potato leaves and tubers were also determined. The results showed that the *Manate blanc* variety recorded the best collar diameter (2.96 ± 0.49 cm). *Dosa*, *Manate violet* and *Cipira* varieties had the lowest incidence (7.60, 9.67 and 13.42% respectively), while *Wouzang* variety had the highest incidence (90%). The severity was low for the *Cipira*, *Mondiale*, *Dosa* and *Manate violet* varieties (2; 7, 9 and 11% respectively). The best yield was obtained from the *Dosa* variety (42.09 ± 2.52 t. ha⁻¹). In terms of biochemical parameters, *Bamso* variety produced the lowest phenolic compound content (2.13 ± 0.32 µg/g PF) compared than *Manate violet* variety (5.29 ± 1.52 µg/g PF). Phenylalanine ammonia-lyase (PAL) enzyme activity was highest in leaves of the *Manate blanc* variety (182.72 ± 59.87 ΔA 290/min/mg) and in tubers of the *Mondiale* variety (439.51 ± 81.59 ΔA 290/min/mg). Polyphenol oxidase (PPO) activity was high in leaves and tubers of the *Panamera* variety (5.45 ± 0.69 and 3.44 ± 0.70 ΔA 330/min/mg respectively). The *Cipira* and *Dosa* varieties, with their low incidence and severity of late blight and good yields, may be the best suited for an integrated disease management strategy.

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1. Introduction

Potatoes (*Solanum tuberosum* L.) are of great economic and social importance both nationally and worldwide

The potato production cycle is mainly vegetative, with the tubers produced serving as an organ of asexual reproduction, the food part of the plant and a raw material for industrial processing [1]. In recent years, its worldwide production has risen from 328,616,920 tons in 2010 of 18,167,194 hectares to 370,436,581 on 17,340,986 ha in 2019 [2], making it the fourth most important crop after maize, wheat and rice. In Cameroon, potato cultivation has been introduced in certain agro-ecological zones since the 19th century and it occupies a very privileged place among marketed tubers. In 2019, 363,556 tons of potatoes were produced in an area of 21,471 ha in nine out of ten Cameroonian regions [3]. Therefore, importance of potato's to the national economy, total production remains below the optimal potential. Several factors contribute to yield losses, such as the use of local varieties with low production potential, the unavailability of quality tuber seeds, pest and disease attacks. Among parasitic attacks, late blight is the most destructive and dreaded disease by potato growers [4]. It is caused by the Oomycete *Phytophthora infestans* (Mont.) [5]. This Oomycete is able to attack all organs of an infected plant. Yield losses caused by this disease can reach 100% in less than three weeks. Potato crops can be completely destroyed when conditions are conducive to the pathogen's development [6]. Chemical control, with the use of contact or systemic fungicides, remains the main measure for controlling potato late blight [4]. However, the management of these diseases with these fungicides is generally limited due to the development of resistance by populations of the pathogen or vector agents [7]. The reduced efficacy of metalaxyl and maneb against late blight, has been demonstrated in Cameroon [8, 9]. It is therefore necessary to intensify genetic control, in which many programs are based on the introduction of resistance genes [10], with the aim of selecting varieties with good agronomic value and resistance to pests and diseases. These programs are based on the introduction of a specific, single-gene resistance [11]. Similar genes have also been identified in other species of *Solanum tuberosum*, such as *S. bulbocastanum* [12, 13], *S. berthaultii* [14], *S. phureja* [15] or *S. michoacanum* [16].

Indeed, plants naturally develop resistance to biotic and abiotic stresses by activating preformed defenses and induced mechanisms. The triggering of the hypersensitive response (HR) of host plants following pathogen attack leads to the activation of induced

mechanisms that are associated with local changes at the site of infection [17]. The hypersensitive response is one of the most effective forms of plant defense, causing an accumulation of antimicrobial compounds such as phenolics and phytoalexins, and an increase in the activity of peroxidases and polyphenol oxidase enzymes involved in defense responses [18, 19-21]. The hypothesis tested in this work is that the so-called improved and local varieties of potato grown in Cameroon possess little-known characteristics and may respond differently to infection by *P. infestans* in the field through the natural activation of defense mechanisms. The aim of this study was to determine the natural response of potato varieties to *P. infestans* infection.

2. Materials and methods

2.1. Study site

The experiment was carried out in fields in the locality of Babadjou (623307 N and 628303 E). This locality belongs to agro-ecological zone 3, known as the Western Highlands zone of Cameroon. Rainfall is monomodal, ranging from 1,700 to 2,000 mm/year. The soil is ferralitic hydromorphic [22]. The research was conducted during the rainy season (between March and June) in 2023.

2.2. Experimental design and culture condition

A Fisher completely randomized Block Design (CRBD) with three replicates was used to screen potato varieties. Each block consisted of 12 experimental units delimited by a distance of 1 m and 2 m between blocks. Planting was carried out manually, with an equivalent tuber seeding rate of 1.2 t/ha and an average density of 50,000 plants per hectare. Plant spacing was 60 cm x 30 cm, and planting depth 7 to 10 cm. A mixture of fertilizers (urea 130 kg/ha, triple superphosphate 400 kg/ha and potassium sulphate 200 kg/ha) was applied to the soil before sowing to restore fertility [23]. Manual weeding was carried out every two weeks, starting 21 days after sowing (DAS). No phytosanitary treatments were applied, in order to encourage the natural infection of the plots by disease and to be able to judge the behavior of the varieties during vegetation. The size of the experimental plot was 164 x 10 m.

2.3. Assessment of the agronomic parameters

Agronomic parameters including stem collar

diameter, plant height, and number of leaves were evaluated at 3, 6 and 9 weeks after sowing (WAS). Stem collar diameter was determined using a caliper at 5 cm above ground level; height was determined using a meter, and leaves were determined for each variety by exhaustive counting. The parameters were measured for six plants per plots. Also, the tuber emergence rate was evaluated at 2, 3 and 4 days after sowing (DAS) and the percentage of tuber emergence was determined according to the formula:

$$\text{TEr (\%)} = \text{NTEr}/\text{NTS} \text{ [4].}$$

TEr = Tubers emerged (%); NTEr = Number of tubers emerged; NTS = Number of tubers sown.

2.4. Evaluation of epidemiological parameters

In the vegetation phase, the evaluation of plant infection by disease focused on its incidence and severity. Disease incidence or expansion rate is the frequency with which the disease appears on plants in a plot; it will be determined at 6; 8; 9 weeks after sowing (WAS) and expressed as a percentage according to the formula:

$$I (\%) = n/N \times 100 \text{ [24].}$$

I (%) = Disease incidence; n = Number of infected plants in the plot; N = Total number of plants in the plot.

Disease severity or intensity of disease infection in the plants of each plot. It is estimated on the basis of the proportion occupied by characteristic disease symptoms in the aerial parts of the plants. It was also determined at 6; 8 and 9 WAS and then calculated as a percentage (%) according to the formula proposed by Tchoumakov and Zaharova [24]:

$$S (\%) = \sum (ab)/N \times 100$$

S (%) = Severity of infection; a = Number of diseased plants; b = Degree of infection corresponding to diseased plants; N = Total number of diseased plants.

The degree of infection is graded according to the standard 0 to 4 scale [4]. Where 0 = [1 to 20 %]; 1 = [20-40 %]; 2 = [40-60%]; 3 = [60-80 %]; 4 = [80-100 %]

2.5. Biochemicals markers analysis

Tubers and leaves of the 12 potato varieties (4 months old) on which late blight was observed, were collected for determination of total phenols, proteins and

certain antioxidant enzymes.

2.5.1. Determination of content of total phenolic compound

Extraction and quantitative measurement of the total phenolic compounds were performed as described by Tene et al., [25]. Total phenolic compounds were extracted twice using 80% methanol. One gram of fresh potato leaves was ground in 3 mL of 80% methanol at 4°C. After 5 min of agitation, the ground material was centrifuged at 10,000 g for 5 min at 4°C. The supernatant was collected, and the pellet was re-suspended in 5 mL of 80% methanol followed by agitation for 5 min. After the second centrifugation at 4°C, the supernatant was collected and mixed with the previously collected supernatant to constitute the phenolic extract. The concentration of phenolic compounds was determined spectrophotometrically at 725 nm according to the method of Singleton and Rossi [26], using the Folin-Ciocalteu reagent. Total phenolic content was expressed as mg equivalent of gallic acid per g of fresh weight.

2.5.2. Determination of the content of total protein

To determine the total native protein content, extraction was performed as described by Tarafdar and Marschner [27] with some modifications. Potato leaves (1 g) and tubers (1 g) were ground with polyvinylpyrrolidone (PVP) under cold conditions. The sample material was mixed in 0.75 ml of Tris-maleate buffer (0.1 M) [0.5 M Tris-base, 0.3 M ascorbic acid, EDTA (0.1% w/v), Triton X-100 (0.1% v/v), LiCl (17% w/v) and pH 7.2].

The samples were incubated for 40 min at 4°C and then centrifuged at 4500 rpm (Thermo Fisher Scientific centrifuge) for 15 min at 4°C. The collected supernatant was used as the crude extract.

The proteins were quantified using the Bradford [28] method. One mL of Bradford reagent was added to each mL of extract. The absorbance was measured at 595 nm using a UV-VIS 1605 Shimadzu spectrophotometer. BSA was used as the standard. Total protein contents were expressed in mg eqBSA/g fresh weight.

2.5.3. Evaluation of enzymes activities

Polyphenoloxidase (PPO) activity was quantified in the total native protein extract as described by Van Kemmen and Broumer [29] using catechol as a substrate. The enzyme activity was expressed as $\Delta A_{330}/\text{min/g}$

Table 1. Variation in emergence rate by variety

Varieties	2 WAS	3 WAS	4 WAS
Bamso	69.00 ± 12.73ab	90.75±8.13ab	91.50±9.19a
Cipira	72.50 ± 10.61ab	97.50±0.71a	98.00±0.00a
Desiree	65.00 ± 14.14ab	91.00±1.41ab	95.50±0.71a
Dosa	46.00±5.66bc	91.50±9.19ab	98.50±2.12a
Manate blanc	77.50±3.54a	89.50±0.71ab	100.00±0.00a
Manate violet	65.50±0.71ab	86.00±1.41ab	99.50±0.71a
Mogbing	70.00±7.07ab	85.00±0.00abc	89.50±13.44a
Mondiale	67.50±10.61ab	98.50±0.71a	96.50±4.95a
Moremeking	23.50±4.95c	27.50±3.54d	55.00±14.14b
Pamela	29.50±3.54c	32.00±0.00d	57.50±3.54b
Panamera	25.50±0.71c	70.00±2.83c	86.00±5.66a
Wouzang	66.50±2.12ab	81.50±3.54bc	97.50±3.54a
F. value	12.96	72.68	10.91
P. Value	<0.001***	<0.001***	0.000129 ***

WAS= Weeks after sowing; Values in the same column, followed by the same letter, are not significantly different at the 5% degree-of-freedom threshold.

protein. POX activity in the total native protein extracts was determined according to the method described by Rodriguez and Sanchez [30]. The enzyme activity was expressed in ΔA 420/min/g protein. Phenylalanine ammonia-lyase (PAL) activity was assessed according to the method was described by Okey et al., [31] using phenylalanine as substrate. The enzyme activity was expressed as ΔA 290/min/g protein.

2.6. Yield assessment

To assess tuber susceptibility to late blight, the harvest from each elementary plot was sorted and classified into three categories: yield in terms of the number of tubers and weight of infested tubers (tubers with one or more mildew spots); marketable yield (healthy tubers with a size greater than 28 mm); total yield (infested tubers + marketable tubers + waste) [4].

2.7. Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) using R software version 4.0.1. The data tested followed a normal distribution (Shapiro-Wilk test; $P > 0.05$) as did homogeneity of variance (Levene test; $P > 0.05$). The multiple comparison of means in the case of growth and yield parameters were determined and the Tukey HSD test followed the analysis of variance when, significant differences ($P < 0.05$) for any of the factors were detected. Means of biochemical parameters were grouped for comparison using the Scott and Knot [32] test.

Principal component analysis (PCA) and clustering of each parameter were run for the effect of agronomic parameters, biochemical compounds in potato leaves and tubers.

3. Results

3.1. Tuber emergence rate

The results showed that the tuber emergence rate varied between the varieties (Table 1). At 2 WAS, emergence rate was 23.5% for *Moremeking* variety and 77.5% for *Manate blanc* variety. At 4 WAS, the *Moremeking* variety had an emergence rate of 55.0% and the *Manate blanc* variety an emergence rate of 100 % (Table 1). A significant difference was recorded at 2 WAS (F-value = 12.96; $P < 0.001$), 3 WAS (F-value = 72.68; $P < 0.001$) and 4 WAS (F-value= 10.91; $P = 0.000129$).

3.2. Stem diameter

Observations of the changes in stem diameter showed variation over time and variety (Table 2). A significant difference was observed at 3 WAS (F-value = 4.61; $P < 0.001$). At this time, the largest stem diameter was obtained by the *Manate blanc* variety (1.16 ± 0.11 cm) and the smallest by the *Mogbing* variety (0.26 ± 0.11 cm). At 9 WAS (F-value = 24.80; $P < 0.001$), *Dosa* recorded the largest stem diameter (2.96 ± 0.49 cm), followed by *Panamera* (2.64 ± 0.33 cm).

3.3. Plant height

The evolution of plant height showed variety-

Table 2. Variation in stem diameter by variety

Varieties	3 WAS	6 WAS	9 WAS
Bamso	0.42±0.05b	0.73±0.16cd	1.68±0.18efg
Cipira	0.52±0.20b	1.02±0.20bc	1.60±0.14fg
Desiree	0.63±0.4b	1.13±0.10b	1.72±0.19ef
Dosa	0.67±0.36ab	1.17±0.36b	2.96±0.49a
Manate blanc	1.16±0.11a	1.66±0.11a	1.94±0.2de
Manate violet	0.61±0.18b	1.11±0.18b	2.26±0.25c
Mogbing	0.26±0.11b	0.71±0.15d	1.20±0.20h
Mondiale	0.58±0.11b	1.08±0.11b	2.10±0.29cd
Moremeking	0.54±0.15b	1.03±0.15bc	2.14±0.18cd
Pamela	0.74±0.29ab	1.24±0.30b	1.40±0.14gh
Panamera	0.58±0.19b	1.32±0.44b	2.64±0.33b
Wouzang	0.44±0.27b	0.62±0.11d	1.10±0.19h
F. value	4.612	6.644	24.8
P. value	<0.001***	<0.001***	<0.001***

WAS= Weeks after sowing; Values in the same column, followed by the same letter, are not significantly different at the 5% degree-of-freedom threshold.

Table 3. Variation in plant height by variety

Varieties	3 WAS	6 WAS	9 WAS
Bamso	6.2±1.64a	10.8±2.77ab	26.0±2.65bcd
Cipira	5.6±1.52ab	12.6±1.14ab	22.8±2.59cd
Desiree	4.4±2.51ab	11.8±0.45ab	37.8±6.22a
Dosa	4.4±1.14ab	11.4±2.70ab	34.4±1.52ab
Manate blanc	5.2±1.64ab	12.0±1.87ab	32.2±16.60ab
Manate violet	6.2±1.095a	11.2±2.28ab	23.2±6.61cd
Mogbing	6.0±1.87a	11.2±2.77ab	31.2±4.87abc
Mondiale	5.2±2.68ab	9.6±4.40b	20.8±7.60d
MoremeKing	3.4±0.89b	4.6±1.52c	26.4±5.59bcd
Pamela	5.2±2.28ab	13.0±1.22a	20.6±6.95d
Panamera	4.0±1.58ab	12.6±3.05ab	22.6±4.67cd
Wouzang	5.0±1.73ab	12.4±1.34ab	18.4±3.66d
F value	1.21	4.536	3.993
P (>F)	0.306 ns	0.000108***	0.000376***

Values in the same column, followed by the same letter, are not significantly different at the 5% degree-of-freedom threshold.

dependent variation at 3 (F-value = 1.21; $P > 0.306$), 6 (F-value= 4.53; $P = 0.000108$) and 9 (F-value= 3.99; $P = 0.000376$) WAS (Table 3). At 6 WAS, the highest plant height was obtained by the *Pamela* variety (13.0±1.22 cm) and the lowest by the *Moremeking* variety (4.6±1.52 cm). On the other hand, at 9 WAS, the *Desiree* variety (37.8±6.22 cm) recorded the highest height than the *Wouzang* variety (18.4±3.66 cm).

3.4. Number of leaves

The number of leaves increased over time and variety (Table 4). A significant difference between varieties were recorded for parameters. At 9 (F-value= 10.41; P

< 0.001) WAS, the *Manate blanc* variety produced the highest number of leaves (23.8±2.49 leaves), followed by *Panamera* (23.00±3.00 leaves), *Pamela* (14.4±3.3 leaves) and *Bamso* (14.8±2.17 leaves) varieties.

3.5. Incidence of late blight

Observation of the evolution of disease incidence showed variation over time and according to variety (Fig. 1). Late blight incidence ranged from 7.60% to 90 % at 9 WAS. During this period, *Dosa*, *Manate violet* and *Cipira* varieties had the lowest incidence (7.60, 9.67 and 13.42% respectively), while *Panamera*, *Mogbing* and *Wouzang* varieties had the highest (73,

Table 4. Number of leaves by variety

Varieties	3 WAS	6 WAS	9 WAS
Bamso	6.8±1.79ab	12.0±0.71d	14.8±2.17g
Cipira	4.4±1.14bc	12.4±0.55cd	18.6±1.14cde
Desiree	6.2±0.87abc	9.6±0.55ef	16.0±2.12efg
Dosa	4.4±2.19bc	12.8±1.30cd	20.8±2.39bc
Manate blanc	4.6±0.89abc	16.8±4.32a	23.8±2.49a
Manate violet	6.6±2.30abc	14.4±1.34bc	20.0±1.22cd
Mogbing	3.4±0.89c	11.6±1.14de	18.4±2.41cde
Mondiale	6.6±1.34abc	12.4±1.14cd	15.6±1.14fg
MoremeKing	5.0±0.00abc	9.4±1.51f	16.4±1.82efg
Pamela	5.2±2.68abc	8.6±1.67f	14.4±3.36g
Panamera	7.8±1.30a	15.2±0.84ab	23.0±3.00ab
Wouzang	5.8±0.84abc	12.8±1.10cd	17.6±1.14def
F value	3.451	10.54	10.31
P (>F)	0.00136 **	<0.001***	<0.001***

Values in the same column, followed by the same letter, are not significantly different at the 5% degree-of-freedom threshold.

80.20 and 90% respectively).

3.6. Severity of Potato late blight

The evolution of severity showed a variation over time and according to variety (Fig. 2). Significant differences were observed ($P < 0.05$) for each period (3, 6 and 9WAS). At 9 WAS, the varieties *Cipira*, *Mondiale*, *Dosa* and *Manate violet* varieties showed the lowest severity (2, 7, 9 and 11% respectively), while the *Banso*, *Moremeking* and *Wouzang* varieties showed the highest severity (27, 23 and 11% respectively).

3.7. Variation of biochemical parameters of potato varieties under late blight control

3.7.1. Variation of biochemical parameters in screened potato leaves

The screened potato varieties showed variability in the biochemical parameters assessed in their leaves

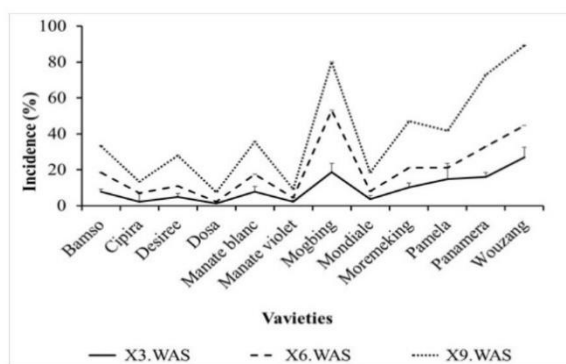


Figure 1. Incidence of potato late blight according to variety.

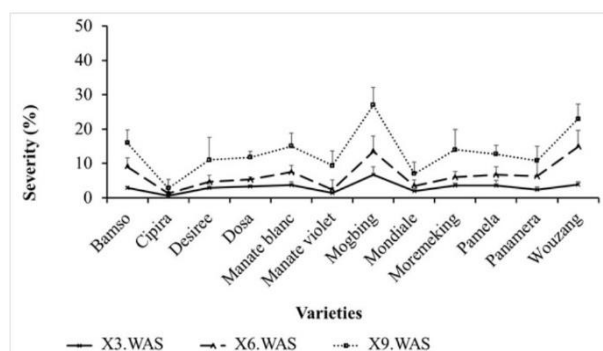


Figure 2. Severity of potato late blight according to variety.

(Table 5). With regard to phenols, the *Bamso* variety produced the lowest phenolic compound content ($2.13 \pm 0.32 \mu\text{g/g FW}$) and the *Manate violet* variety the highest phenolic compound content ($5.29 \pm 1.52 \mu\text{g/g FW}$). In terms of protein, *Pamela* ($8.63 \pm 0.18 \mu\text{g/g FW}$), *Panamera* ($7.75 \pm 1.54 \mu\text{g/g FW}$) and *Mondiale* ($7.03 \pm 1.36 \mu\text{g/g FW}$) varieties had the highest levels. PAL enzyme activity was higher in *Manate blanc* variety ($182.72 \pm 59.87 \Delta\text{A } 290/\text{min/mg}$) than in *Wouzang* ($182.46 \pm 72.32 \Delta\text{A } 290/\text{min/mg}$) and *Mogbing* ($182.72 \pm 59.87 \Delta\text{A } 290/\text{min/mg}$) varieties. POX activity is high in *Mondiale* variety ($1.85 \pm 0.85 \Delta\text{A } 420/\text{min/mg}$) and PPO in *Panamera* variety ($5.45 \pm 0.69 \Delta\text{A } 330/\text{min/mg}$).

3.7.2. Variation in biochemical parameters in screened potato tubers

In potato tubers, the production of biochemical markers varied among varieties (Table 6). Protein

Table 5. Variation of biochemical markers in screened potato leaves

Varieties	PT	Prot	PAL	POX	PPO
Bamso	2.13±0.32b	5.82±1.39b	528.40±81.59b	0.23±0.03b	1.63±0.71b
Cipira	4.33±0.37a	4.23±0.43b	424.71±84.97b	1.51±0.13a	4.73±1.13a
Desiree	4.20±0.52a	5.24±0.29b	251.85±51.32c	0.55±0.17b	4.90±2.49a
Dosa	3.89±0.98a	5.50±0.36b	237.04±90.12c	0.46±0.19b	3.27±0.76b
Manate blanc	4.67±1.16a	5.03±0.92b	886.42±85.53a	1.38±0.42a	2.93±0.50b
Manate violet	5.29±1.52a	5.89±1.23b	400.64±50.10b	1.22±0.13a	3.91±0.38a
Mogbing	5.23±0.35a	5.20±0.13b	182.72±59.87c	0.41±0.08b	3.04±0.28b
Mondiale	3.76±0.26a	7.03±1.36a	390.12±86.52b	1.85±0.85a	4.12±0.48a
Moremeking	3.57±1.02a	6.30±0.89b	437.81±89.47b	0.21±0.07b	3.53±0.72b
Pamela	1.23±0.43b	8.63±0.18a	202.47±56.09c	1.54±0.39a	5.14±0.93a
Panamera	2.60±0.24b	7.75±1.54a	464.20±66.80b	0.56±0.07b	5.45±0.69a
Wouzang	2.83±0.79b	4.15±1.27b	182.46±72.32c	0.98±0.33b	2.54±0.59b
F value	6.98	5.75	28.12	6.18	4.19
P	<0.001***	0.000172***	<0.001***	0.00195**	0.00165**

PT: Total Phenols et Prot: Proteine (–µg/g fresh weight), enzymatic Activity (PAL: Phenylalanine ammonia-lyase, POX: Peroxidases PPO : Polyphenol oxidase in -ΔA/min/mg fresh weight). The values followed by the same letter in the column are not significantly different in the Scott knott test at (P < 0.05).

Table 6. Variation of biochemical markers in screened potato tubers

Varieties	PT	Prot	PAL	POX	PPO
Bamso	0.67±1.02a	3.41±0.60ab	138.27±61.68b	0.15±0.03a	1.05±0.13b
Cipira	1.83±0.47a	3.53±1.08ab	165.49±61.15b	0.68±0.39a	1.97±0.38b
Desiree	1.93±0.77a	4.10±0.22ab	44.44±14.81b	0.36±0.05a	0.90±0.21b
Dosa	2.49±0.36a	3.92±0.17ab	138.27±17.11b	0.24±0.12a	0.94±0.09b
Manate blanc	1.75±0.93a	4.74±0.97a	51.85±12.22b	0.39±0.32a	1.16±0.16b
Manate violet	2.83±0.86a	3.95±0.69ab	129.00±22.47b	0.57±0.07a	0.87±0.21b
Mogbing	0.96±0.94a	3.94±0.90ab	335.80±54.84a	0.14±0.03a	0.86±0.26b
Mondiale	1.36±0.24a	5.03±1.13a	439.51±81.59a	0.34±0.07a	1.37±0.10b
Moremeking	1.15±0.42a	2.79±1.21b	311.11±46.41a	0.09±0.01a	1.10±0.30b
Pamela	1.61±0.45a	4.64±1.46a	105.53±24.99b	0.42±0.06a	0.99±0.31b
Panamera	3.22±0.34a	2.69±0.60b	161.19±28.51b	0.24±0.07a	3.44±0.70a
Wouzang	1.46±1.06a	3.26±0.9ab	137.15±37.38b	0.30±0.05a	0.82±0.90b
F value	2	1.981	7.043	2.528	10.87
P	0.0755	0.0482	<0.001***	0.063ns	<0.001***

PT: Total Phenols et Prot : Protéine (–µg/g fresh weight), enzymatic Activity (PAL: Phenylalanine ammonia-lyase, POX : Peroxidases PPO : Polyphenol oxidase in -ΔA/min/mg fresh weight). The values followed by the same letter in the column are not significantly different in the Scott knott test at (P < 0.05).

content was higher in *Mondiale* (5.03 ± 1.13 µg/g FW), *Manate blanc* (4.74 ± 0.97 µg/g FW) and *Pamela* (4.64 ± 1.46 µg/g FW) varieties than in *Panamera* (2.69 ± 0.60 µg/g FW) and *Moremeking* (2.79 ± 1.21 µg/g FW) varieties. PAL activity was higher in *Mondiale* (439.51 ± 81.59 ΔA 290/min/mg), *Mogbing* (335.80 ± 54.84 ΔA290/min/mg) and *Moremeking* (311.11 ± 46.41 ΔA 290/min/mg) varieties than in all other varieties. In terms of PPO activity, the *Panamera* variety (3.44 ± 0.70 ΔA 330/min/mg) had a high PPO content compared

with all the other varieties, which produced statistically the same PPO content.

3.8. Variation in yield by variety under late blight control

A significant difference (P < 0.05) was observed between the yield parameters of the different varieties (Table 7). The highest number of apparently healthy tubers was obtained by the *Dosa* variety (27.67 ± 7.79 tubers), followed by the *Manate Blanc* variety (20.67 ± 4.93 tubers) compared with the *Panamera* variety (5.83

Table 7. Variation in yield by variety

Varieties	NAHPT.P	NDPT.P	MY.ha	NMY.ha	TY.ha
Banso	18.50±5.09bc	0.17±0.10d	14.33±1.97cde	0.04±0.02d	14.37±2.06fg
Cipira	16.00±7.56bcd	0.17±0.08d	42.00±2.51a	0.09±0.07d	42.09±2.52a
Desiree	12.33±3.39de	1.17±0.7cd	21.67±2.29c	1.68±1.00bcd	23.35±2.71d
Dosa	27.67±7.79a	4.00±2.53a	32.24±8.53b	3.69±1.53a	35.93±11.97b
Manate Blanc	20.67±4.93b	3.17±2.04ab	15.67±1.06cde	2.77±1.54ab	18.45±1.01def
Manate Violet	13.33±2.25cd	0.33±0.26cd	32.33±6.48b	0.41±0.32cd	29.41±10.85c
Mogbing	7.00±2.37ef	1.67±1.37cd	20.07±4.89cd	1.71±1.25bcd	21.77±4.07de
Mondiale	7.33±3.14ef	0.50±0.26cd	17.30±0.39cde	0.68±0.46cd	17.97±0.72def
Moremeking	12.33±3.72de	1.83±1.47bc	12.03±0.76e	2.04±0.97abc	14.07±0.94fg
Panamera	5.83±1.47f	1.50±1.22cd	13.49±1.83de	2.76±1.56ab	16.25±2.30efg
Pamela	10.33±3.93def	0.33±0.30cd	10.38±2.69e	0.09±0.17d	10.46±2.74g
Wouzang	11.00±3.41def	0.33±0.34cd	12.75±2.54de	1.56±1.11bcd	14.30±1.79fg
F value	11.88	6.333	41.51	4.792	21.41
P	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***

NAHPT.P: Number of apparently healthy potato tubers per Plant, NDPT.P: Number of Disease Potato Tubers per Plant, MY.ha : Marketable Yield in tons per hectare, NMY.ha : Non-Marketable Yield in tons per hectare, TY.ha: Total Yield in tons per hectare, Values in the same column, followed by the same letter, are not significantly different at the 5% degree-of-freedom threshold.

± 1.47 tubers). The highest number of diseased tubers was also recorded in the *Dosa* and *Manate Blanc* varieties (4.00 ± 2.53; 3.17 ± 2.04 respectively). The highest commercial yield (42.00 ± 2.51 t/ha) was obtained in *Cipira* variety. The highest non-commercial yield was recorded for the *Dosa* variety (3.69 ± 1.53 t/ha). Total yields in tons per hectare were 42.09 ± 2.52 t/ha for *Cipira* and 10.46 ± 2.74 t/ha for *Pamela* variety.

3.9. Multivariate analysis

3.9.1. Principal component analysis

Principal Component Analysis (PCA) (Fig. 3) showed the closeness of potato varieties to growth parameters, biochemical parameters, disease incidence and severity, in potato leaves, tubers and yields. The visualized dispersion of the two main components (PC1 and PC2) explained 44.6 % of the total variation in the system and contained more information and graphically summarized genotypes performance about late blight infection. The varieties *Banso*, *Mogbing*, *Moremeking*, *Pamela*, and *Wouzang* are closer to the incidence (Inc) and severity (Sev) of the disease with a trend away from the different biochemical markers of resistance assessed (Ph.L, Prot.L, PAL.L, POX.L, PPO.L, Ph.T, Prot.T, PAL.T, POX.T, PPO.T). On the other hand, the varieties *Cipira*, *Desiree*, *Dosa*, *Manate blanc*, *Manate violet*, *Mondiale* and *Panamera* are

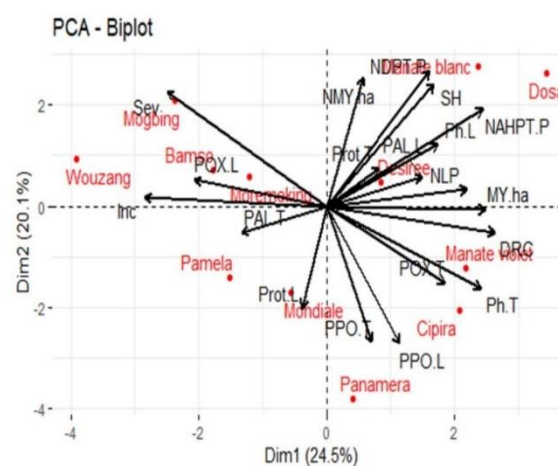


Figure 3. Principal component analysis – biplot of evaluated parameters.

(LR: Lift Rate, DRC: Diameter at Root Collar , SH: Stem Height, NLP: Number of Leaves per Plant, Inc: Incidence, Sev: Severity, NAHPT.P: Number of apparently healthy potato tubers per Plant, NDPT.P: Number of Disease Potato Tubers per Plant, MY,ha : Marketable Yield in tons per hectare, NMY,ha : Non-Marketable Yield in tons per hectare, Ph,L : Total Phenol in leaves, Prot,L : Total Proteins in leaves, PAL,L : Phenylalanine ammonia-lyase in leaves, POX,L : Peroxidases in leaves, PPO,L : Polyphenol oxidases in leaves, Ph,T : Total phenols in Tuberbercules, Prot,T : Proteins in Tuberbercules, PAL,T: phenylalanine ammonia-lyase in Tuberbercules, POX,T: Peroxidases in Tuberbercules, PPO,T: Polyphenol oxidases in Tuberbercules).

very close in terms of yield (NAHPT.P, NDPT.P, MY.ha, NMY.ha) and resistance markers.

3.9.2. Hierarchical clustering analysis of different parameters

The classification of these varieties according to the different parameters studied using a cluster (5% dissimilarity) showed six groups (Fig. 4). The first group consists of a single variety (*Wouzang*), the second of *Moremeking*, *Mogbing* and *Bamso*, the third *Mondiale* and *Pamela*. Overall, this analysis revealed that *Cipira* and *Manate violet* are the most resistant varieties to late blight, while *Wouzang*, *Moremeking*, *Mogbing* and *Bamso* are the most susceptible.

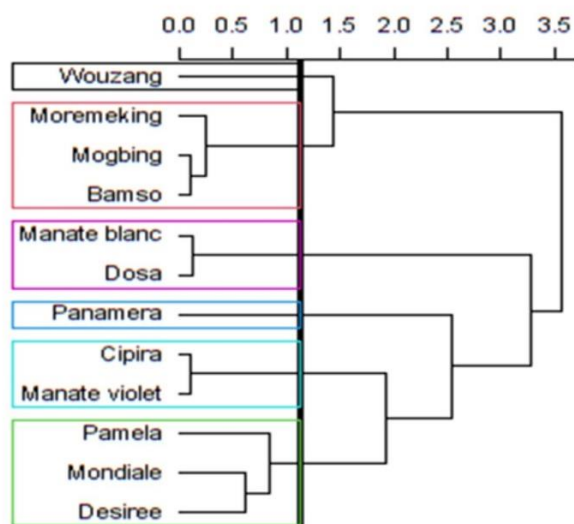


Figure 4. Classification cluster of different varieties according to parameters.

4. Discussion

The emergence rates of potato tubers of the different varieties in the field were more or less high on all plots at 4 weeks after sowing (WAS). *Moremeking* and *Pamela* varieties had the lowest emergence rates (55% and 57% respectively), while the other varieties had emergence rates of over 80%. Significant variations of the same type were also observed by some researchers such as Giri et al., [33] who showed that the highest emergence rates were registered by the variety PRP 146871.20 followed by PRP 016567.6, CIP 303381.106, *Desiree* and the lowest emergence rate was found by local variety *Jumli* at 30 days after sowing. Observations of changes in collar diameter showed a variation over time in the different potato plant varieties. At 9 WAS, the *Wouzang* and *Mogbing*

varieties had the smallest diameters. In terms of plant height, the results showed that plant heights vary from 18.4 to 37.8 cm for the *Wouzang* and *Desiree* varieties respectively. Results for the average number of leaves for each variety showed that the *Manate blanc* variety followed by the *Panamera* variety had the highest number of leaves, while the *Bamso* and *Pamela* varieties had the lowest. The variability observed in plant growth is thought to result from genetic variation among the potato genotypes tested [34]. Many authors have shown that growth parameters vary according to potato genotype [35-38]. These varieties are genetically different in their growth mode, which effects the number of leaves per plant, stem height and collar diameter.

Berhanu and Tewodros [39] reported a highly significant effect of environment and cultivar on the number of leaves per plant and potato plant height in eastern Ethiopia. Also, Bandjade [40] reported substantial variability in plant height between potato genotypes in northern Ethiopia. These differences in heights, leaf numbers and neck diameters between varieties may also be due to plant material quality, seed tuber size, environmental variations, agronomic practices, plant spacing [37, 41]. Observation of the evolution of plot infection rates by the disease shows variation over time and according to variety.

Incidences of late blight ranged from 7.60% to 90% at 9 WAS. The *Dosa* variety, *Manate violet* followed by the *Cipira* variety showed the lowest incidences compared with the other varieties, with the highest rates in the *Panamera*, *Mogbing* and *Wouzang* varieties. Significant differences were observed between degree of disease infection (severity) for each observation period (3; 6 and 9 WAS). At 9 WAS, the varieties *Cipira*, *Mondiale*, *Dosa* and *Manate violet* showed the lowest severity, while the varieties *Banso*, *Moremeking* and *Wouzang* showed the highest severity. Glen-Karolczyk et al., [42] demonstrated that, the intensity of infectious diseases in potato tubers is the result of a number of coinfluencing factors: environmental; agro-technical and biotic interactions between organisms that colonize the tubers. According to principal component analysis, the variation in disease severity is correlated with the variation in the expression of biochemical markers involved in plant defense against pathogens. A decrease in disease

severity is associated with an increase in the synthesis of biochemical compounds involved in plant defenses. The potato leaves and tubers screened showed variability in the production of biochemical compounds. In leaves, the *Banso* variety produced the lowest phenolic compound content and the *Manate violet* variety the highest phenolic compound content in both leaves and tubers. Indeed, phenolic compounds constitute a very important group of secondary metabolites involved in pathogen resistance. According to Lorenc-Kukula et al., [43], phenolic compounds are present in potato flowers, leaves and tubers, imparting antimicrobial properties. In terms of protein, the varieties Pamela, *Panamera* and *Mondiale* have the highest protein content in the leaves. In tubers, the protein content was higher in the *Mondiale* variety, than in the *Panamera* variety. The variation in protein production in leaves and tubers is thought to be due to the level of infection by the pathogen. The *Banso*, *Moremeking* and *Wouzang* varieties were the most susceptible to the disease. Many authors stipulate that these proteins are encoded and cannot be expressed when the plant is stressed by pathogen infection or elicitors [44, 45]. PR proteins can inhibit pathogen growth and/or spore germination and act as antimicrobial agents, hydrolases and proteinase inhibitors [46]. With regard to oxidative enzyme activity, phenylalanine ammonia-lyase (PAL) was very high in the leaves of the *Manate blanc* variety than in the *Wouzang* and *Mogbing* varieties. POX activity was high in *Mondiale* and PPO in *Panamera*. In potato tubers, PAL activity was high in the *Mondiale* variety and PPO activity was high in the *Panamera* variety. Ngadze et al., [47] showed high PAL, PPO and POD activity conferring resistance to soft rot in *S. tuberosum*. PAL enhances cinnamic acid production [48] which can induce the expression of defense-related genes. PPO confers disease resistance to plants by hydroxylating monophenols to ortho-diphenols, which are toxic to pathogens [49]. De Ascensao and Dubery [50] demonstrated that peroxidase (POX) is linked to the host plant's defense response and is involved in strengthening the plant cell wall. The production of PPO and POX in screened potato varieties can prevent chemical and biological attacks by reinforcing physical barriers or by counter-attacking a

microorganism through the strong generation of free radicals [51].

In addition, several studies have shown that good plant health has a significant impact on production yield [52, 53]. This study showed that the number of apparently healthy tubers differed between the varieties. *Dosa* variety followed by the *Manate Blanc* variety had the highest number of tubers per plant. Habtamu et al., [54] showed that the number of tubers per plot depends mainly on the number of stems per plot, the total number of runners that tuberize. Total yields in tons per hectare varied according to the variety and the commercial yield was obtained from *Cipira* variety. The highest commercial yields were observed in the *Cipira*, *Dosa* and *Manate violet* varieties, while the lowest yields were observed in the *Banso*, *Moremeking*, *Panamera*, *Pamela* and *Wouzang* varieties. The variation in total yield of potato genotypes at different locations may be due to the responses of genotypes and environmental factors. Glen-Karolczyk et al., [42] demonstrated that hydrothermal conditions prevailing during the growing season are the main determining factor in plant yield, in particular, root vegetables with a long growing season and high water demand. This suggestion is in line with other authors who have shown that yield differences between genotypes are attributed to both the inherent yield potential of genotypes and the growing environment, as well as to genotype x environment interactions [55]. Similarly, other researchers have also shown that marketable yield varies significantly with variety, location and genotype x environment interactions [56, 57]. Also, genotype variation in non-marketable yield may be due to the following factors adaptability, crop maturity and the inherent ability of potato genotypes to produce non-marketable tubers per plant [54]. The result of the non-marketable yield of potato varieties in the present work is consistent with the findings of Hammerschmidt and Kuc [58], who reported that the interaction effects of the growing environment and genotype significantly influence non-marketable tuber yield. Habtamu et al., [54] also reported similar significant differences between genotypes in phenological and growth characteristics, tuber yield, tuber physical characteristics and internal quality from the evaluation of 16 potato genotypes in eastern

Ethiopia. Indeed, the expression of a given trait can be the result of interaction between genetic factors and the plant environment.

Principal component analysis and cluster carried out on all the agro-morphological variables of the potato lines showed that, out of the eight descriptors adopted, two proved to be the most discriminating according to Fisher statistic (F) values greater than 10: yield parameters and epidemiological parameters. The varieties *Cipira*, *Desiree*, *Dosa*, *Manate blanc*, *Manate violet*, *Mondiale* and *Panamera* are very similar in terms of yield and resistance markers. They are more resistant to late blight, while the *Wouzang*, *Moremeking*, *Mogbing* and *Bamso* varieties are the most susceptible. Infection of potato plants by the disease triggers the activation of natural defense mechanisms, which vary from variety to variety [59]. The triggering of this resistance by *P. infestans* infection reinforces the plant's innate defense mechanism [60].

5. Conclusions

At the end of the study, it was found that the vegetative conditions and development of the lines differed in the field. Desire and Dosa were the variety that performed the best vegetative state. As for varietal behavior with regard to late blight, the expression of tolerance varied significantly between the different varieties tested. *Manate* and *Cipira* were the most tolerant to late blight, while *Wouzang*, *Mogbing*, *Moremeking* and *Pamela* were the most susceptible. With regard to yield, there was considerable variability between the lines, for all yield parameters. *Cipira* varieties, with 42.09 t.ha⁻¹, were the most productive, while *Pamela* varieties were the least productive. This study revealed significant variability among released potato varieties in their tuber yield and resistance to late blight. This suggests a greater chance of using these genotypes to improve resistance, tuber yield and other important agronomic traits in the crossing program.

Authors' contributions

Ousman abdraman collect data in field and write the first draft of manuscript, Sylvere Landry Lontsi Dida collect data, writing and editing, Alain Heu collect data in field and read, Patrice Zemko Ngatsi formal analysis and editing, Paul Martial Tayo Tene make lab

experimentation and editing, Landry Thierry Voukeng Dongmo, Benoit Constant Likeng Li-Ngue, Joseph Martin Bell read and editing.

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Availability of data and materials

All data will be made available on request according to the journal policy.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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