Effects of Soil Amendments on Incidences of Bacterial Wilt and Tuber Yield of Potato at Different Environments in Malawi

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Abstract
This study investigated the effects of soil amendment on potato yield and incidences of bacterial wilt caused by *Ralstonia solanacearum* that can cause up to 80% yield loss in potato. The research was conducted at four research stations in Malawi during the 2020/21 and 2021/22 growing seasons, using a randomized complete block design (RCBD) with six treatments: lime, four Calciprill rates (CALC25%, CALC50%, CALC100%, and CALC150%), and NPK fertiliser (control). Data on soil properties, bacterial wilt incidence, and potato tuber yield were collected and analyzed using R programming. Soil fertility was found to be low, with a pH range of 4.4 - 6.05. Control resulted to significantly higher incidences of bacterial wilt at Kandiyani during 2020/21 (63.6%) and 2021/22 (34.6%) and at Lunyangwa during 2021/22 (20.4%) while lime and all levels of Calciprill led to relative incidence reduction (4 – 89%) across sites and season, except CALC25% at Bembeke. Marketable yield showed interaction between amendments and season at Bvumbwe ($p = 0.04$), highest being 10.02 tha^{-1} in CALC150% during 2020/21 while non-marketable yield showed interaction at Lunyangwa ($p = 0.02$) highest being 3.9 tha^{-1} recorded in CALC150% during 2021/22. A significant negative correlation between bacterial wilt incidences and yield at all sites except Bembeke highlighted the importance of controlling bacterial wilt for yield improvement. The findings suggest that soil amendment through liming is an effective and sustainable approach for managing bacterial wilt and increasing potato yields. Further research on-farm conditions required to ensure the applicability of the findings for different sites.

Key words: *Amendment; Potato; Soil; Disease incidence; Bacterial wilt*

1. Introduction

Potatoes play a vital role in providing both food and income for farmers in Malawi, being the third most important food crop after maize and cassava, and serving as the main source of income in the primary production regions [1]. The potato's short growth cycle, usually 90 days or less, makes it suitable as a bridging crop providing food prior to maize maturation and enabling two to three production cycles in a given year, providing calories and income throughout the year. Malawi ranks as the second-highest producer in the Southern Africa Development Community (SADC) region, with an average production volume of 1.8 million tons from 2017 to 2021, behind only South Africa [2]. In light of the unmet market demand [1], potato production is expected to expand and is already extending into areas that have not traditionally produced this crop (Mwenye et al., 2022). To address the supply deficit, it is imperative to close the significant yield gap (where the average yield of farmers is 18.3 tons per hectare, while existing improved varieties range from 18 to 40 tons per hectare [3], which is attributed to among other factors pests and diseases including Bacterial Wilt.

Potato bacterial wilt, caused by the bacterium *Ralstonia solanacearum*, has a significant impact on both the quality and yield of potato and it is a major threat to potato production in many parts of the world including Africa [5]. The disease reduces the plant's ability to absorb water and nutrients, leading to wilting as the major symptom and eventual plant death [5–7]. This results in significant yield losses, with some studies indicating reductions of up to 80% in affected fields [8] which can have serious economic consequences for farmers, especially in regions where potatoes are a primary food and cash crop. The pathogen, *R. solanacearum* is soilborne and is usually spreads through contaminated irrigation water, rain drop splashes, contaminated vegetative propagating material such as tubers and farm equipment [9].

Potato bacterial wilt incidence and severity is known to be exacerbated under environmental conditions such as moisture situation [10], low soil pH [11] and generally low soil fertility [12]. Tafesse et al., (2021) found that the incidence of potato bacterial wilt was high in potato fields with a low soil pH in Ethiopia and Li et al., (2017) reported that the proportion of *R. solanacearum* infection was higher in soils with pH lower than 5.5. Low soil pH restricts the availability of important nutrients for crops, resulting in weak and vulnerable plants that are more susceptible to infection from pathogens [14]. Cao et al., (2022) found that soils that were less conducive to the disease had higher concentrations of soil organic carbon (SOC), total nitrogen, available potassium, and available phosphorus when compared to soils that are more prone to disease.

Given the lack of any effective chemical control measures, the primary strategy for preventing bacterial wilt is to use pathogen-free planting material and maintain field hygiene and crop rotation [5]. Unfortunately, most farmers (about 90%) in Malawi source planting materials from uncertified sources such as recycling own seed or open market [1], which increases the risk of disease. Recent soil surveys show that many soils in potato growing regions are acidic and low in fertility, which makes them more susceptible to bacterial wilt disease [15] In this context, it is crucial to enhance soil fertility and raise the soil pH to suppress *R. solanacearum* in potatoes. Application of soil amendments including lime ($CaCO_3$ or $CaMg(CO_3)_2$), organic fertilizers, biochar, and mineral fertilizers has been shown to alter soil microbial biomass, activity, and community composition, enhance crop vigour and suppress bacterial wilt disease in other regions [12, 16, 17]. However, no such studies have been conducted in Malawi to determine the effects of soil amendments on bacterial wilt incidence and severity or to develop recommendations for farmers. This study aims to quantify the effect of locally sourced agricultural lime ($CaCO_3$; just referred to as lime) and Calciprill (a granulated sulfur and calcium carbonate shortened to CALC in this study) on bacterial wilt incidence and potato yields in major potato growing districts in Malawi. The result of this study provides valuable information to help farmers combat bacterial wilt disease and improve potato yields.

2. Materials and methods

2.1. Site

On-station experiments were established at four research stations namely Kandiyani, Bembeke and Bvumbwe and Lunyangwa representing two main agroecological zones in Malawi, the mid and high altitude [18]. Kandiyani is a substation of Chitedze research station located in Lilongwe, 13°55′ S and 33°39′E, in the mid altitude zone and receives 900 mm annual rainfall. Soils are dominantly ferruginous alfisols with a mean pH of 5.1 (ranging 4.5 – 6 pH). Bembeke research is in Dedza district, 14º 35′S , 34º 43′ E at 1600 meters above sea level (masl) and receives mean annual rainfall of more than 1500mm, soil are sandy clay loam (SCL) and strongly acid (< 4.5). Bvumbwe is located 13 km southeast of Blantyre; 15º55' S, and 35º04' E and 1,146 masl; receiving 1,219 mm mean annual rainfall; soils are sandy clay loams and strongly acidic (pH 4.4-5.0). Lunyangwa is located in Mzuzu, receiving mean annual rainfall of 1270 mm and soils are generally acidic (pH 4.4 -5.6).

2.2. Trial Layout and Treatment

The study was conducted for two seasons during 2020/21 and 2021/22 cropping season. Six treatments including: lime, four rates of Calciprill, and a control were laid in a randomized complete block design (RCBD) replicated three times. Agricultural lime was applied using recommended rate of two (2) tons per hectare (tha^{-1}). While in Calciprill, we set 800 $kgha^{-1}$ after reviewing literature. Treatments used and their description are summarised in Table 1:

Table 1. Treatments and their detailed description

	Treatment	Description
i.	CALC150%	Calciprill applied at 150% (1200 kg/ha) of 800 kg/ha rate + NPK fertiliser
ii.	CALC100%	Calciprill applied at 100% (800 kg/ha) of the 800 kg/ha rate + NPK fertiliser
iii.	CALC50%	Calciprill applied at 50% (400 kg/ha) of the 800 kg/ha rate + NPK fertiliser
iv.	CALC25%	Calciprill applied at 25% (200 kg/ha) of the 800 kg/ha rate + NPK fertiliser
v.	Lime	Recommended Lime application rate (2 tha^{-1}) + NPK fertiliser
vi.	Control	NPK fertiliser alone

Plot size was 18.75 m^2 composed 5 ridges, each 5 m long spaced at 0.75 cm to which disease-free potato seed tubers of variety Violet were planted.

2.3. Soil amendments application and Planting

During planting, ridges were opened to make a farrow deep enough, about 15 cm that will accommodate seed potato tubers. Calciprill, lime and NPK basal fertiliser, D compound (10% Nitrate (N), 20% Phosphorus Oxide (P_2O_5), 10% Potassium (K_2O), Sulfur (S) + Zinc (Zn)) at a rate of 250 $kgha^{-1}$ was broadcasted and mixed with soil (S1). Well sprouted seed potato tubers were then placed on a ridge at a spacing of 30 cm apart. The ridge was then reconstructed, making sure tubers were properly covered with soil.

2.4. Crop management

Weeding was carried soon weeds appeared in the fields and hilling up of the ridges was conducted twice or more. All potato plots including control were top dressed using Calcium Ammonium Nitrate (CAN) fertiliser 200 $kgha^{-1}$, 14 days after emergency. Cypermethrin was applied to protect plant from aphids and other pests while a preventive fungicide, Dithane was applied every fortnight, increasing frequency during wet periods to protect the crop from late blight.

2.5. Disease monitoring and crop yield assessment

Complete or partial wilting was considered as the main symptom of bacterial wilt disease during vegetative stage. Bacterial wilt assessment in the field started with the onset of first wilt symptoms. Plants that showed either complete or partial wilting (S2) were all considered wilted and continuously staked to avoid double counting in subsequent assessments and also to avoid the possibility of missing out those that completely die early in the growth period. Number of wilted plants was recorded at 70 DAP. Bacterial wilt incidence was then calculated as percentage of total number of plants emerged. Relative response to amendments was calculated by subtracting incidences (%) in the plots with treated with lime and Calciprill from incidences in control plot (equation 1). A positive or negative result denotes the effectiveness of soil amendments over control in reducing or increasing disease incidence, respectively.

Harvesting was conducted when 75 – 100% of the plants showed senescence. Harvested tubers were graded into non-marketable (< 35 mm in diameter) and marketable (> 35 mm) (S3). Rotten tubers were counted and expressed as a percentage of total number of either marketable or non-marketable. Statistical data analysis was performed using R Programming 4.0.3 [19].

3. Results

3.1. Soil properties

Soil analysis results showed that soils in all stations acidic ranging from slightly to strongly acidic and were mostly low in N, P and K content (Table 2) as referenced to the critical values by Snapp [20] and ratings by [21] for Malawi soils. Soils pH below 5.2 are considered acidic and SOC, N, P and K levels below 0.8%, 0.1%, 13 mgkg^{-1} and 0.2 Cmol/Kg are considered low for proper growth of plants [20]. At Kandiyani soils were moderately acidic with pH level for top (5.65) and subsoil (6.05) above the critical value, P (3.28 ug/g) and K (0.01 Cmol/Kg) were also low except OC, N, and Ca levels were all above the critical levels with soils being classified as sandy loamy. At Bvumbwe, soils were also acidic, pH level for topsoil (5.04) below critical value and K was also low for both top and subsoil, 0.03 Cmol/kg below critical value while the rest of other measured properties were above critical values with the soil texture classified sand loamy (Table 2). Soils at Lunyangwa were strongly acidic, with pH of 4.53 for topsoil and 4.44 for subsoil, topsoil OC (1.19%) was above the critical value and topsoil N (0.1%) was just within adequate range while rest of the properties were below critical values with soils classified as sandy loam. Similarly at Bembeke soils were strongly acidic but other properties were within the adequate ranges (Table 2).

Table 2. Levels of key soil properties for the experimental fields for at different research stations. Critical soil test values used; pH =5.2, OC =0.8%; N = 0.1%, P = 13 mg kg-1, K = 0.2 Cmol/Kg, CA 0.2 Cmol/Kg [20].

Properties	**Depth**	**Site**				**Critical Value**
		Kandiyani	**Bvumbwe**	**Lunyangwa**	**Bembeke**	
	0-20	5.65	5.04	4.53	4.61	5.2
pH	**20-40**	6.05	5.23	4.44	4.85	
	0-20	1.83	1.53	1.19	1.73	0.8
% OC	**20-40**	1.65	1.55	0.52	1.46	
	0-20	0.16	0.13	0.1	0.15	0.1
%N	**20-40**	0.14	0.13	0.05	0.13	
	0-20	3.28	19.56	3.94	27.32	13
P (ug/g)	**20-40**	1.34	13.39	1.34	7.41	
	0-20	0.01	0.03	0.04	0.02	0.2
K (Cmol/Kg)	**20-40**	0.01	0.03	0.03	0.03	
	0-21	0.51	0.86	0.69	0.54	0.2
Ca (Cmol/Kg)	**20-41**	0.58	0.69	0.58	0.55	
	0-22	13	17	13	15	
% Clay	**20-42**	11	13	13	9	
	0-23	12	12	10	4	
% Silt	**20-43**	10	14	12	16	
	0-20	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	
Tex. Class	**20-40**	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	

3.2. Bacterial wilt incidences

The impact of soil amendments on the occurrence of bacterial wilt differed depending on the season and the location, as shown in Table 3.

The incidence of bacterial wilt on plants and tubers at Kandiyani was significantly influenced by the season, with a higher percentage of affected plants (31.3%) observed in 2020/21 compared to 2021/22 (12.6%; $p < 0.001$). Soil amendments had significant effect on bacterial wilt incidence. The control plot recorded highest percentage of wilted plants, 63.6% and 34.6% during 2020/21 ($p = 0.003$) and 2021/22 ($p < 0.001$) respectively, while the plots treated with different levels of lime and Calciprill did not show any significant differences. A significant interaction between the season and soil amendments was observed in the percentage of rotten tubers (p = 0.02), with the control plots recording the highest percentage of rotten tubers (46.3% in 2020/21) and the lowest percentage observed in the plots treated with CALC150% and lime (Table 3). In 2021/22, the control plots did not differ from the plots treated with CALC25% in terms of the percentage of rotten tubers. When compared with the control plots, all the plots treated with lime and different levels of Calciprill showed a reduction in bacterial wilt incidence, ranging from 38% to 89% across the seasons (Figure 1).

At Bvumbwe research station, the incidence of bacterial wilt was significantly influenced by soil amendments in the 2020/21 season (p <0.001), with the lowest incidence recorded in the plots treated with CALC150% (0.8%), which did not differ significantly from those treated with CALC100% (3.6%), while the control plots had the highest incidence (12.1%). The percentage of rotten tubers was also lowest in the plots treated with CALC150% (4.8%), CALC100% (4.4%), and lime (5.26%), while the control plots had the highest percentage (12.1%) in the 2020/21 season. In the 2021/22 season, there was no significant effect of soil amendments on the incidence of bacterial wilt, either in terms of the percentage of affected plants or rotten tubers. Nevertheless, all plots amended with lime showed a reduction in bacterial wilt incidence in both seasons, with reductions ranging from 25% to 93% (Figure 1).

At Lunyangwa research station, the incidence of bacterial wilt was significantly influenced by the season, with a higher incidence recorded in the 2020/21 season. In the 2021/22 season, lime application resulted in the lowest incidence of only 3.6%, while the control plots recorded the highest incidence of 20.4% (p < 0.001). For tubers, the control plots in 2020/21 had the highest percentage (47.6%) of rotten tubers compared to the rest (p = 0.002). However, all soil amendments resulted in a reduction of bacterial wilt incidence across seasons, ranging from 16% to 82% (Figure 1).

A significant interaction was observed between season and treatments at Bembeke research station (p = 0.007). In the 2020/21 season, soil amendments had a significant effect on bacterial wilt incidence, with lime and CALC150% resulting in the lowest incidence of wilted plants (5.8% and 13.2%, respectively) compared to control (25.4%; p = 0.009). The percentage of rotten tubers was also lowest in Lime (27.9%), CALC 150% (17.9%), and CALC 100% (28.3%) compared to control (46.1%; p = 0.04). Across the season, all other treatments resulted in a negative response to bacterial wilt incidence due to soil amendments, resulting in a reduction in incidences ranging between 4% and 77%, except for CALC25% in the 2020/21 season (Figure 1).

Table 3. Effects of soil amendment on bacterial wilt disease incidence (%)

Season	Treatment	Kandiyani		Bvumbwe		Lunyangwa		Bembeke	
		Wilted Plants	**Rotten Tubers**	**Wilted Plants**	**Rotten Tubers**	**Wilted Plants**	**Rotten Tubers**	**Wilted Plants**	**Rotten Tubers**
2020/21	CALC150%	18.8±15.7^{b}	8.5^{c}	0.8±1.4^{d}	4.8^{c}	12±3.8	13.4^{c}	13.2±5.9^{b}	17.9^{b}
	CALC100%	21.5±9.3^{b}	14.8^{bc}	3.6±0.1^{cd}	4.4^{c}	11.7±3.8	14^{c}	16.3±7^{a}	31.4^{ab}
	CALC50%	23.2±3^{b}	21.5^{bc}	7.6±2.5^{b}	10.5^{b}	12.4±3.3	15.8^{bc}	16±8.6^{ab}	28.3^{b}
	CALC25%	38.9±6.4^{b}	27.6^{b}	8.6±3^{ab}	13.2^{ab}	13±3.9	31^{b}	26.5±6.1^{a}	32.6^{ab}
	Lime	21.8±20^{b}	7.3^{c}	5.7±2^{bc}	5.16^{c}	12.3±0.8	14.7^{c}	5.8±1.3^{b}	27.9^{b}
	Control	63.6±5.9^{a}	46.3^{a}	12.1±2^{a}	17^{a}	15.7±1.4	47.6^{a}	25.4±4^{a}	46.1^{a}
	Mean	**31.3**	**21**	**6.4**	**9.19**	**12.8**	**22.8**	**17.3**	**30.7**
	CV	**37.3**	**44.8**	**30.8**	**26.7**		**39**	**34.5**	**28.3**
	P Value	**0.003**	**0.002**	**<0.001**	**<0.001**	**Ns**	**0.002**	**0.009**	**0.04**
2021/22	CALC150%	3.5±2.1^{c}	4.8^{c}	17.7±2	15.6	8.6±0.8^{c}	3.5	8.3±0.9	0.66

CALC100%	8.7±6[c]	8.1[bc]	16.3±8	13.4	10±1.6[bc]	6.1	8.3±3.6	3.89
CALC50%	5.2±5[c]	4.8[c]	21.2±5	17.7	13.7±2.7[b]	5.2	11.9±2.4	2.25
CALC25%	19.7±5[c]	12.8[ab]	21.2±8	23.5	9.4±1.6[c]	8	8.9±4	12.55
Lime	4.5±2[b]	7.2[c]	21.9±13	12.3	3.6±2.4[d]	6	10.9±4	2.04
Control	34.6±5[a]	18.3±[a]	29.2±6	25.6	20.4±2.8[a]	7.5	12.5±2.3	16.01
Mean	**12.6**	**9.3**	**21.2**	**18**	**11**	**6**	**10.2**	**6.2**
CV	**35.9**	**33.1**			**19.2**			
P Value	**< 0.001**	**0.001**	**ns**	**ns**	**<0.001**	**ns**	**ns**	**ns**
Season	< 0.001	< 0.001	<0.001	<0.001	0.02	< 0.001	<0.001	<0.001
Season x Treatment	ns	0.02	ns	ns	0.001	0.001	0.007	ns

Means with different superscripts within the same column are significantly different (LSD $_{0.05}$). Numbers typed after ± are standard deviation (SD), ns = non-significant.

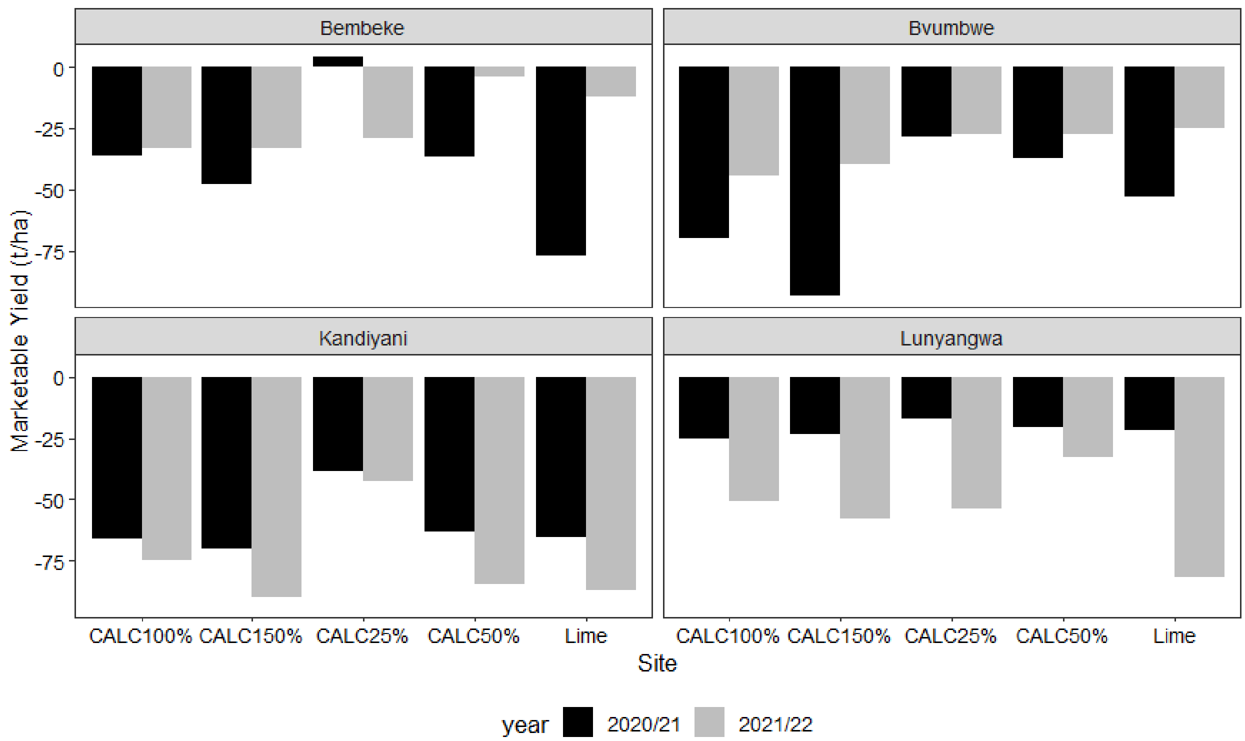

Figure 1. Bacterial wilt incidence response to soil amendments

3.3. Potato tuber yield

The effects of soil amendments on potato tuber yield varied based on season, and site, as shown in Table 4. At Kandiyani, non-marketable tuber yield was not affected by either season or soil amendments. However, the mean marketable tuber yield was significantly influenced by both soil amendments ($p < 0.001$) and season, with a higher yield recorded in 2021/22 (8.5 tha^{-1}) compared to 2020/21 (5 tha^{-1}) ($p < 0.001$). In 2020/21, CALC150% resulted in the highest marketable tuber yield (7.3 tha^{-1}), followed by lime and CALC100%, while the lowest yield was recorded in the control plots (2.9 tha^{-1}), although it did not differ from CALC25% and CALC50% (Table 4). In 2021/22, the highest marketable tuber yield was obtained in plots treated with lime (11.5 tha^{-1}) and CALC150% (9.9 tha^{-1}), while the lowest was obtained in the control (5.1 tha^{-1}).

Similarly, at Bvumbwe, non-marketable tuber yield was not influenced by either season or soil amendments (Table 4). However, marketable tuber yield showed an interaction (p = 0.04) between season and soil amendments, with the highest yield of 10 tha^{-1} recorded in lime plots during the 2020/21 season. At Lunyangwa, non-marketable tuber yield showed an interaction (p = 0.04) between soil amendments and season, with the highest yield of 3.9 tha^{-1} recorded in CALC50% during the 2021/22 season. Marketable tuber yield was not influenced by soil amendments at Lunyangwa during both growing seasons. While at Bembeke, both non-marketable and marketable tuber yield showed an interaction between season and soil amendments (Table 4). For non-marketable tubers, the highest yield was obtained in the lime treatment, 3 tha^{-1} during the 2021/22 season. For marketable tubers, the highest yield was obtained in CALC 150% (5.3 tha^{-1}) during the 2021/22 season.

Table 4. Effects of soil amendment on marketable and non-marketable tuber yields of potato across different sites ($kgha^{-1}$)

Season	Treatment	Kandiyani		Bvumbwe		Lunyangwa		Bembeke	
		NMT	MT	NMT	MT	NMT	MT	NMT	MT
2020/21	CALC150%	2.1±1.2	7.3±1.5^{a}	1.4±0.4	6.22±2.3^{ab}	1.9±0.2	3.3±1.1	1.8±0.8	5.3±0.9^{a}
	CALC100%	2.9±1.8	5.4±0.8^{b}	1.5±0.7	8.1±2.9^{a}	2.7±0.6	3.1±0.7	1.5±0.5	3.3±0.4^{bc}
	CALC50%	2.8±1.5	4.2±1.5^{bc}	1±0.4	5.8±0.6^{ab}	2.3±0.6	2.2±0.6	1.8±0.4	2.4±0.6^{c}
	CALC25%	2.9±0.5	4.3±0.5^{bc}	1.7±0.1	5.7±4^{ab}	2.1±0.7	3.4±0.2	1.7±0.1	3.6±0.6^{b}
	Lime	2.9±0.3	5.6±0.2^{b}	1.9±0.7	10±2.6^{a}	1.8±1	1.8±1.6	1.5±0.5	3.8±0.2^{b}
	Control	2.4±0.1	2.9±0.2^{c}	1.3±0.4	2.1±0.4^{b}	2.7±0.7	3±0.2	1.7±0.6	1.3±0.1^{d}
	Mean	**2.7±**	**5.0**	**1.4**	**6.3**	**2.3**	**2.8**	**1.6**	**3.3**
	CV		**17.8**		**39.4**				**17.1**
	P Value	**ns**	**0.001**	**ns**	**0.03**	**Ns**	**ns**	**ns**	**<0.001**
2021/22	CALC150%	2.9±0.4	9.9±1.5^{ab}	0.9±0.4	8.1±1.3	3.9±0.1^{a}	2.7±0.3	1.5±0.2^{b}	2.4±0.2
	CALC100%	2.2±0.2	8.3±0.7^{b}	1.4±0.7	4.3±2.8	2.6±0.5^{bc}	3.2±0.4	0.9±0.2^{b}	1.6±0.7
	CALC50%	3.4±1.2	8.0±1.1.9^{b}	1.4±0.1	4.6±0.3	2.4±1.2^{bc}	2.3±0.4	0.9±0.3^{b}	1.9±0.9
	CALC25%	2.7±0.3	8.1±1.2^{b}	1±0.6	4.2±3	1.5±0.4^{cd}	2.6±0.6	1.2±0.4^{b}	1.7±0.8
	Lime	2.9±0.9	11.5±1.4^{a}	1.1±0.2	4±1.4	3.2±0.5^{ab}	8.3±8	3±0.5^{a}	2±0.2
	Control	2±0.06	5.1±1^{c}	0.9±0.2	3.3±0.5	0.9±0.6^{d}	2.3±1.7	1.2±0.3^{b}	1.5±0.2
	Mean	**2.7**	**8.5**	**1.1**	**4.7**	**2.4**	**3.6**	**1.4**	**1.8**
	CV							**25**	
	P Value	**ns**	**0.001**	**ns**	**ns**	**0.001**	**ns**	**<0.001**	**Ns**
Season		**ns**	**<0.001**	**ns**	**ns**	**<0.001**	**ns**	**ns**	**Ns**
Season x Treatment		ns	ns	ns	0.04	0.02	ns	0.007	<0.001

Key: NMT - Non-marketable tuber yield, MT- Marketable Tuber yield. Means with different superscripts within the same column are significantly different ($LSD_{0.05}$). ns = non-significant

3.4. Relationship between bacterial wilt incidence and tuber yield

Figure 2 summarizes the results of a regression analysis conducted to explore the association between bacterial wilt incidence and potato tuber yield. The findings revealed that there was a significant negative correlation between the incidence of bacterial wilt and potato marketable tuber yield at Bvumbwe ($p = 0.004$, $R^2 = 0.26$), Kandiyani ($p < 0.001$, $R^2 = 0.52$), and Lunyangwa ($p = 0.004$, $R^2 = 0.16$) (Figure 2), except at Bembeke. The results suggest that an increase in bacterial wilt incidence by one unit would lead to a reduction in marketable yield of 0.15 at Bvumbwe, 0.1 at Kandiyani, and 0.24 at Lunyangwa.

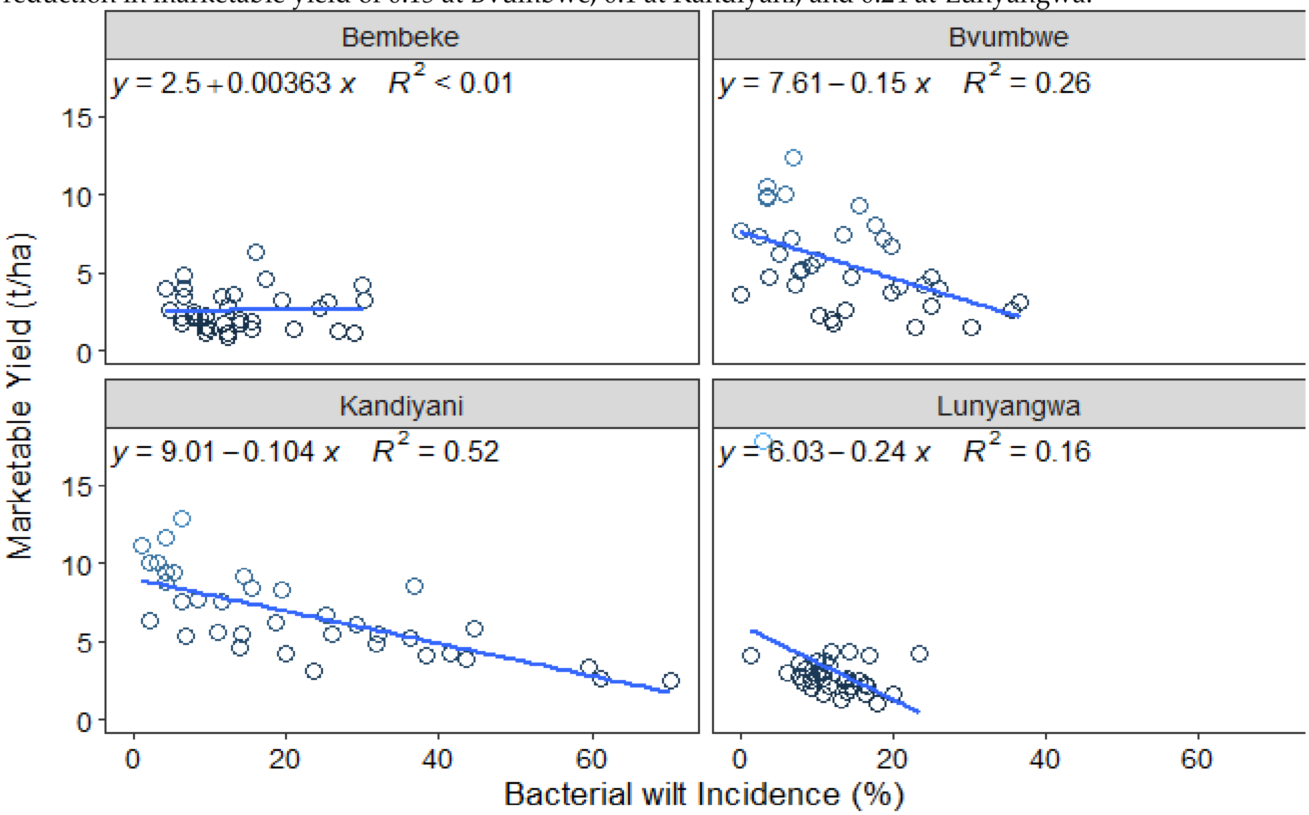

Figure 2. Relationship between tube yield and bacterial wilt incidence

4. Discussion

4.1. Soil Condition and Plant Diseases

The soil plays a critical role in potato production by providing the necessary environment and nutrients for growth and productivity, and its quality significantly impacts crop productivity. Soils are home to a variety of fauna, including microorganisms, some of which are beneficial, while others can cause plant diseases like *R. solanacearum* [22]. In healthy soils with balanced nutrients, water conditions, and microbiomes, disease-causing agent's activities are suppressed, allowing plants to resist disease development. Unfortunately, soils in Malawi, including those in potato producing regions are typically impoverished and deficient in essential elements necessary for crop growth, like N, P, and K, and are under significant threat from soil erosion resulting in a loss of approximately 29 tons/ha per year [23]. Soil pH is also an essential property that affects several factors, including availability other nutrient and toxicity to plants. Our study found that most soils in our sites, including Kandiyani, Bembeke, Bvumbwe, and Lunyangwa, have low pH, a widespread issue in Malawi that exacerbates bacterial wilt infection in potatoes. Other studies also indicated that acidity is widespread in Malawi, with a considerable percentage of farms having pH values lower than the critical limit [15, 24]. Therefore, our study is highly relevant. Soil amendments such as lime, biochar, and compost manure have been used to improve soil fertility and disease suppressive ability. However, due to the prevailing acidic conditions of most soils in Malawi, we focused on the application of lime, which is commonly used to neutralize soil acidity by reacting with hydrogen ions (H+) in the soil, releasing calcium ions (Ca2+) that replace the hydrogen ions and raising soil pH. Calcium ions also improve soil structure by increasing aggregation, which improves water and nutrient retention in the soil. Furthermore, the presence of calcium promotes the growth of microorganisms and beneficial soil fauna, which further improve soil health and fertility. Our study utilized agricultural lime, commonly found in Malawi, and Calciprill, a new soil amendment that is portable and easy to apply in addition to mineral fertilizer.

4.2. Effects of soil amendments on bacterial wilt incidences

This study found that the effectiveness of soil amendments in reducing bacterial wilt incidences varied across different sites and seasons, which could be due to differences in moisture conditions and initial *R. solanacearum* inoculum. Nonetheless, the results provide further evidence that treating soils with powdered agricultural lime or Calciprill (granulated CaCO3) potentially reduces bacterial wilt incidences. In sites and seasons where the effects of soil amendments were significant, applying lime and Calcipril along with mineral fertilizer led to reduction in bacterial wilt incidences compared to amendment with mineral fertilizer alone. Even when the effects of soil amendments were not significant, application of lime and different levels of Calcipril still resulted in a reduction in the occurrences of bacterial wilt in comparison to solely using mineral fertilizer. The most effective outcomes were seen in Lunyangwa and Bembeke by applying lime, and in Kandiyani and Bvumbwe by using CALC150%, both with high application rates. These findings align with previous research on the positive effect of lime application on soil pH and the reduction in bacterial wilt incidences [13]. Even at lower application rates, our study recorded a relative reduction of bacterial incidences in all sites and across seasons compared to mineral fertilizer alone. This highlights the importance of reducing bacterial wilt incidence through soil amendments, which provides farmers with an additional sustainable option for managing the disease in addition to using clean planting material and field hygiene, leading to increased potato productivity.

The seasonal effects on bacterial wilt incidences in most sites could be attributed to weather conditions and *R. solanacearum* populations in the soil. Research has shown that pathogen incidences are positively associated with total bacterial densities and soil moisture, with soil moisture, total bacterial density, and soil pH being the most significant predictors of pathogen densities [25]. The continuous heavy rains received during the potato vegetative growth period in the 2020/21 cropping season across most regions, including Kandiyani, Lunyangwa, and Bembeke, could explain the resulting high bacterial wilt incidence, which may have been due to excessive soil moisture. Based on these results, the incidence of bacterial wilt can be predicted at the onset of the season using rainfall forecasts, allowing farmers to be prepared for disease management.

4.3. Tuber yield and Bacterial wilt incidence

The negative relationship between the incidence of bacterial wilt and yield indicates that reducing the incidences of bacterial wilt could potentially increase potato tuber yields. Interestingly, the results of this study have shown that soil amendments, particularly lime and a higher rate of Calciprill, are effective in reducing bacterial wilt incidences. This is significant because increasing the pH value through soil amendment can help restrict the activity of *Ralstonia solanacearum* in the soil and increase soil nutrient availability to the crop, resulting in healthy crops that can tolerate disease infection [26]. The results of this study confirm the potential of liming as a sustainable option for increasing smallholder potato yields in acid-dominated production regions [27].. Reducing bacterial damage and increasing tuber yields through soil amendments can also lead to a reduction in production costs by reducing the volume of pesticides that farmers need to procure and apply. It is important to note that a reduction in pesticide application is necessary for a healthy and sustainable smallholder farming system.

The response of potato tuber yield to soil amendment varied in this study, with the greatest effect observed on marketable tubers. However, the yields obtained were lower than the country average, 18 $t ha^{-1}$ [2] possibly due to the late blight disease caused by the oomycete *Phytophthora infestans*, which affected during tuberization period towards the end of the season [28]. Tuber yield showed an increase with the rate of application, particularly with CALC150%, which recorded higher yields in both seasons in Kandiyani and in the 2020/21 season in Bembeke. This is likely due to the fact that lime application raises the pH value and affects the chemical activities of essential nutrients in the soil. High rates of lime and Calciprill have an instant and stronger positive effect on soil pH [29], making essential nutrients more available to the crop and leading to an increase in potato tuber yield. Overall, the results of this study suggest that soil amendment through liming can be an effective and sustainable method for increasing potato yields and reducing production costs.

4.4. Limitations and Future outlook

The present study primarily focused on *R. solanacearum*, neglecting other potato pathogens like *Phytophthora infestans*, which is also a major concern for potato production and was found to have significant impacts. In future studies, it is recommended to incorporate measures to control *P. infestans* and assess its damage. Additionally, as this study was conducted on-station, it is suggested to extend the research to on-farm conditions to ensure the applicability of the findings. Soil physical properties such as porosity and abiotic factors, such as rainfall, should also be taken into account in addition to soil nutrient status and pH. It is also advised to conduct a follow study on effect of amendment on soil status. The recommendation from this study suggests the use of Calciprill at CALC150% and lime at the current recommended rate for managing bacterial incidence and improving yield.

Conclusion

The study aimed to investigate the impact of applying lime and Calciprill on bacterial wilt incidence and potato yields in Malawi. The findings indicated that there were variations in the incidence of bacterial wilt and potato tuber yields across different sites and seasons. The soil in the study areas was acidic and nutrient-deficient, but applying lime and Calciprill resulted in a significant reduction in bacterial wilt incidence and an increase in marketable potato tuber yield. The study revealed a negative correlation between bacterial wilt incidence and marketable tuber yield, highlighting the importance of controlling bacterial wilt for yield improvement. The findings suggest soil amendment through liming as an effective and sustainable option for increasing potato yields and reducing production costs. Further research is necessary to determine specific amendment options including biochar and compost manure. As well as to carry out on-farm research to adapt the findings to farmers' conditions and assess the cost-benefit of using the amendments.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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