

Research Article

Socio-epidemiological Characterization and Phytosanitary Diagnosis of Southern Blight Caused by *Sclerotium rolfsii* in Vegetable Production Systems in Côte d'Ivoire

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Abstract

Southern blight, or white mold, caused by *Sclerotium rolfsii* (Sacc.), represents an emerging and concerning phytosanitary constraint threatening the sustainability of vegetable production systems in Côte d'Ivoire, particularly in agro-ecological zones with high production density. This study aimed to establish an epidemiological and socio-agronomic diagnosis of the disease, analyze farmers' perceptions, and evaluate local phytosanitary management practices from a sustainability perspective. A multidisciplinary and participatory approach was implemented between 2021 and 2022 across six agro-ecological zones, combining phytopathological surveys on 223 plots, semi-structured interviews with producers, and morpho-diagnostic laboratory analyses. The results revealed a high disease prevalence, affecting 64.57% of the plots, with a maximum incidence of 34.44% and severity reaching 22.59% in the AEZ IV. Tomato (*Solanum lycopersicum*) was the most affected host, followed by eggplant, peanut, and bean. Despite this widespread distribution, farmers' knowledge remained limited. Only 52.91% of the producers recognized the symptoms from the images, and barely 13% could identify characteristic fungal structures (mycelium, sclerotia), which correlated with a high illiteracy rate (72.65%). The observed cultural practices (high-risk crop rotations, empirical fungicide applications, lack of effective prophylactic measures) were largely inappropriate. Multifactorial analyses indicated a significant influence of education level, gender, and geographic zone on farmers' disease knowledge. These findings highlight the urgent need to strengthen farmers' capacities through targeted training, integration of indigenous knowledge, and promotion of integrated management strategies within a context-specific framework for the sustainable management of southern blight in Ivorian vegetable production systems.

Keywords

Sclerotium rolfsii, Southern blight, Vegetable Farming, Farmer Perception, Integrated Disease Management, Epidemiological Diagnosis, Agro-ecological Zones

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1. Introduction

Southern blight, or white mold, is a devastating soilborne fungal disease caused by *Sclerotium rolfsii* (Sacc.), a necrotrophic fungus with a broad host range capable of infecting over 500 plant species in tropical and subtropical regions [1-3]. Its infectious capacity is largely due to the production of sclerotia, which are resistant survival structures that enable the pathogen to persist in warm, moist, and organic matter-rich soils for several years in the absence of a host [4, 5]. Such conditions are common in intensive vegetable cropping systems in West Africa, where the fungus poses an increasing threat to the phytosanitary security of tropical agroecosystems. Disease symptoms typically include rapid wilting, collar necrosis, the presence of white, cottony mycelium, and widespread tissue decay at the plant base, often accompanied by brown to black sclerotia visible in the soil [6, 7]. Yield losses can exceed 50% in susceptible crops [7, 8]. In Côte d'Ivoire, where vegetable farming plays a central role in food security and household income, this pathology is rapidly emerging in high horticultural production zones. It severely affects economically important crops such as tomato (*Solanum lycopersicum*), eggplant (*Solanum melongena*), peanut (*Arachis hypogaea*), and common bean (*Phaseolus vulgaris*), as reported by several studies [9, 10]. Despite its significant impact, the epidemiological dynamics of *S. rolfsii* remain largely unknown in Côte d'Ivoire. Scientific and farmer knowledge is limited by factors including insufficient symptom recognition, confusion with other soilborne diseases, a high illiteracy rate reaching up to 72% [10], and the absence of early diagnostic tools [11, 12]. Risky cultural practices such as inadequate crop rotations, excessive planting density, indiscriminate use of synthetic fungicides, and failure to eliminate infection foci contribute to inoculum buildup in soils [13, 14]. Additionally, climate change, uncontrolled agricultural intensification, and increasing phytosanitary pressure exacerbate the disease problem [14, 15]. In response to this situation, this study adopts a transdisciplinary and integrative approach. This study aims to characterize, across six representative agro-ecological zones of Côte d'Ivoire, the spatial distribution and incidence of southern blight, elucidate the ecological and technical factors influencing its spread, and analyze producers' knowledge and practices regarding disease diagnosis and phytosanitary management. The methodology combines phytopathological surveys, morphological diagnostic analyses, and participatory interviews to generate contextualized empirical data. The primary objectives are to characterize the spatial distribution of the disease, analyze the sociotechnical determinants of its dissemination, assess farmer knowledge and associated phytosanitary practices, and propose adapted agro-ecological management strategies.

2. Methods

2.1. Study of Southern Blight in Smallholder Farming Systems

2.1.1. Selection of Survey Areas

The first phase of this study involved a phytosanitary survey of the main vegetable production areas in Côte d'Ivoire in relation to *Sclerotium rolfsii* infestation. To this end, surveys were conducted from 2021 to 2022 across six agro-ecological zones (AEZ) representative of the national territory. These surveys took place during the primary cropping seasons, namely the major rainy season (June–July), the minor rainy season (September–October), and the off-season (November to February and March to April), in order to maximize the likelihood of detecting the pathogen. Due to the lack of precise data regarding the locations of the active pathogen foci, a mobile survey approach was adopted. The selected zones for the survey were characterized by intense vegetable production and had been previously identified in the literature [10] as severely affected by wilting and root rot caused by *S. rolfsii*. The objective was to identify zones with chronic infections, with a focus on fields that are historically susceptible to *S. rolfsii*-induced wilting, particularly in vegetable crops. To detect potential epidemic outbreaks, the survey was also extended to plots cultivated with other plant species that had not previously been reported as hosts of the pathogen in existing literature. Within each AEZ, localities were selected based on the significance of vegetable production. Inside these localities, villages and fields were chosen randomly, with a minimum of two villages per locality. In each selected village, two fields separated by at least 10 km were visited to ensure the spatial representativeness of the sampling.

2.1.2. Survey in Main Vegetable Production Areas

A field survey was conducted among vegetable producers to characterize their socio-economic context, assess epidemiological parameters related to wilting caused by *S. rolfsii*, evaluate farmers' knowledge of the disease, and identify phytosanitary management practices in place. For this purpose, a structured questionnaire was developed and administered through semi-structured interviews conducted in situ, within production fields, using multiple-choice closed questions. The survey topics primarily covered the history of symptom appearance in the field and locality, the technical itineraries and cultural practices adopted, and farmers' empirical perceptions and knowledge of the disease. The survey was supplemented by collecting information related to the sampled field, the cultivated species (host), and direct observations of the phytosanitary condition of the crops. To evaluate the farmers' ability to recognize the symptoms of southern blight, an illustrated reference guide presenting the characteristic signs associated with *S. rolfsii* was shown before any field visits. This step allowed an estimation of their

familiarity with the disease. Subsequently, joint field surveys were conducted with each farmer to assess their aptitude for visually identifying symptomatic plants, aiming to promote autonomous and sustainable disease management at the smallholder level.

A total of twelve (12) questions relating to knowledge of the disease, disease symptoms, favourable periods and host plants were used to assess the level of knowledge of the disease using a scoring system based [29]. A score of 1 was assigned to a correct answer, and 0 to a wrong answer. A composite knowledge index was calculated by dividing the sum of the scores for each grower by the maximum score. This ratio gave a value between 0 and 100%. The values of the composite knowledge index were classified into three categories. When the index is:

Below 50%: knowledge is poor,

Between 50 and 80%: knowledge is average,

Above 80%: knowledge is good.

Geographic coordinates of the surveyed sites were recorded using a Garmin eTrex 10 GPS device.

2.2. Assessment of Disease Impact

Sample collection was conducted based on the characteristic macroscopic symptoms of southern blight, as reported in the literature [8-16]. The targeted symptoms included foliar wilting, collar necrosis accompanied by a mass of white, cottony mycelium, the presence of immature or mature sclerotia, and ring spots with a light-colored center on the leaves, often associated with progressive yellowing. A systematic visual survey was carried out in each visited plot to identify plants exhibiting signs of foliar decline or yellowing, which are potential indicators of root or collar infection. The suspected plants were then examined at the collar level to confirm the presence of fungal structures characteristic of *S. rolfisii* (mycelium, sclerotia, tissue necrosis). In cases of suspected infestation, five quadrats of 4 m² (2 m × 2 m), arranged in a cross pattern following an X-shaped design, were delineated in the affected field. All plants showing typical symptoms were counted within each quadrat to assess disease incidence. The incidence was calculated as a percentage using the formula described by Kator *et al.* [17]:

$$\text{Incidence (\%)} = \frac{\text{Number of symptomatic plants}}{\text{Total number of plants}} \times 100$$

Disease severity was assessed on a sample of 25 plants per field, with 5 plants randomly selected from each subplot. The evaluation was performed using the scale developed by Valakounakis and Fragiadakis [6], ranging from 0 to 3:

0: no symptoms,

1: necrosis followed by yellowing,

2: necrosis with wilting,

3: complete wilting, defoliation, or death.

The severity index was calculated using the formula described by Paparu *et al.* [11]:

$$\text{Severity Index (\%)} = \frac{\sum \text{Number of plants} \times \text{rating}}{\text{Total number of plants} \times \text{highest rating}} \times 100$$

At the end of the observations, five symptomatic plants (showing lesions on the collar, roots, leaves, or stem) were sampled per field, regardless of the cultivated area. After removing the soil residues, the plants were individually packed in kraft paper envelopes for transport to the laboratory. Sclerotia were extracted using sterile forceps and stored in sterile Eppendorf tubes. All samples were placed in airtight polyethylene bags and kept in a refrigerated cooler. All plant material was transported to the Plant Pathology Laboratory of Félix HOUPHOUËT-BOIGNY University for mycological analyses.

2.3. Statistical Analysis of the Data

Data from the structured surveys were processed using Sphinx Plus software, version 5, while information from informal interviews and direct observations underwent qualitative content analysis. A summary table was prepared to present the vegetable species and varieties sampled, along with the infestation rates by locality. All data were entered and organized using Microsoft Excel version 2021, which was also used for graph generation. The percentages showing high variability were arcsine-transformed to meet the normality assumptions of the statistical analyses. Quantitative data were then subjected to analysis of variance (ANOVA) using the Statistica software, version 12.5. Duncan's post hoc test was applied at a 5% significance level to discriminate statistically different means.

3. Results

3.1. Farmers' Knowledge of Southern Blight and Its Epidemiology

3.1.1. Surveyed Areas and Number of Plots Visited

The distribution of the visited plots was determined by the density of vegetable production and the accessibility of the sites across the different agro-ecological zones (AEZs). The number of plots examined in each zone ranged from 23 to 49, depending on the availability of farms and the concentration of vegetable crops. In total, 223 vegetable farms were surveyed, corresponding to an equivalent sample of 223 interviewed farmers. The representativeness of this sample across the different AEZs was as follows: AEZ I and AEZ V (21.97% each), AEZ II (16.14%), AEZ III (10.31%), AEZ IV (15.25%), and AEZ VI (14.35%). This distribution provided adequate coverage of the study area for the epidemiological analysis of southern blight (Table 1).

Table 1. Summary of the number of surveyed producers and visited plots according to agroecological zones and regions.

Agroecological zones	Regions	Number of surveyed producers	Number of plots visited	Proportion (%)
AEZ I	Agneby Tiassa	11	11	21.97
	Goh	8	8	
	Indenie Djuablin	8	8	
	Les grands ponts	14	14	
	Loh Djiboua	8	8	
AEZ II	Haut Sassandra	18	18	16.14
	Marahoue	10	10	
AEZ III	Nawa	8	8	10.31
	Guemon	12	12	
	Tonkpi	11	11	
AEZ IV	Belier	13	13	15.25
	Iffou	11	11	
	Moronou	10	10	
AEZ V	Bere	9	9	21.97
	Gbeke	19	19	
AEZ VI	Worodougou	21	21	14.35
	Poro	19	19	
	Tchologo	13	13	
Overall total		223	223	99.99

3.1.2. Sociodemographic Characteristics of Vegetable Producers by Agro-ecological Zones

The distribution of producers by gender revealed marked disparities across the different agro-ecological zones (AEZs). In AEZs I, II, IV, V, and VI, men predominated significantly, representing 81.63%, 80.56%, 79.41%, 53.06%, and 59.38% of the respondents, respectively. Conversely, AEZ III exhibited an atypical configuration, characterized by an exclusive predominance of female producers (100%). Overall, men constituted most of the sample, accounting for 63.23% compared to 36.77% for women (Table 2). Analysis of age group distribution indicated a relatively young population structure although all age categories from 18 to over 61 years were represented. The most represented age groups were 36–45 years (36.77%), followed by 26–35 years (29.15%) and 46–55

years (21.08%). The extreme age groups were less represented: young producers aged 18–25 years and those aged 56–60 years each accounted for 4.04%, while producers over 61 years constituted only 0.45%. Marital status analysis highlighted a clear predominance of married individuals across all AEZs. The proportion of married producers ranged from 67.65% to 100%, with no cases of widowhood reported (Table 2). Regarding the educational level, the results revealed a significant deficit in formal human capital. The majority of producers were unschooled (72.65%), with illiteracy rates ranging from 51.02% to 100% depending on the zone. Producers with primary education accounted for only 9.87%, while those with secondary education represented 12.56% (Table 2). Tertiary-level education remained marginal, at just 3.59%.

Table 2. Sociodemographic characteristics of vegetable growers from the different agroecological zones.

Variables	Modalities	Agroecological zones (AEZ)						Overall mean
		AEZ I	AEZ II	AEZ III	AEZ IV	AEZ V	AEZ VI	
Gender	Female	18.37	19.44	100.00	20.59	46.94	40.63	36.77
	Male	81.63	80.56	0.00	79.41	53.06	59.38	63.23
Age	< 18 years old	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	18 to 25 years old	2.04	5.56	0.00	0.00	12.24	0.00	4.04
	26 to 35 years old	20.41	47.22	52.17	44.12	14.29	12.50	29.15
	36 to 45 years old	51.02	36.11	0.00	17.65	42.86	53.13	36.77
	46 to 55 years old	18.37	11.11	21.74	14.71	28.57	31.25	21.08
	56 to 65 years old	4.08	0.00	0.00	14.71	2.04	3.13	4.04
	> 65 years old	2.04	0.00	0.00	0.00	0.00	0.00	0.45
	Unknown	2.04	0.00	26.09	8.82	0.00	0.00	4.48
Marital Status	Single	22.45	25.00	8.70	23.53	18.37	0.00	17.49
	Married	77.55	75.00	91.30	67.65	81.63	100.00	81.17
	Unknown	0.00	0.00	0.00	8.82	0.00	0.00	1.35
Educational Level	Primary education	8.16	11.11	0.00	8.82	18.37	6.25	9.87
	Secondary education	8.16	27.78	0.00	8.82	22.45	0.00	12.56
	Higher education	2.04	2.78	0.00	5.88	8.16	0.00	3.59
	Illiterate	81.63	58.33	100.00	67.65	51.02	93.75	72.65
	Unknown	0.00	0.00	0.00	8.82	0.00	0.00	1.35

3.1.3. Agro-pedological Characteristics of the Surveyed Vegetable Farming Plots

The study of cultivated areas revealed considerable heterogeneity, ranging from micro-plots of 50 m² to large farms exceeding 10,000 m² (1 ha). However, most producers operated on small land units between 50 and 5,000 m² (Table 3). Farms larger than one hectare remained marginal within the sample. Three main types of edaphic environments were identified for vegetable production: lowland soils, riparian zones (riverbanks), and upland soils. The distribution of these environments varied according to the agro-ecological zones (AEZs). The lowlands predominated in AEZs I, II, III, and IV, representing 71.43%, 66.67%, 100%, and 44.12% of the production

sites, respectively (Table 3). Conversely, AEZ VI was characterized by a predominance of upland soils (75%). AEZ IV exhibited a notable proportion of plots located along water-courses (38.24%), reflecting diversified ecosystem use. In terms of soil texture, the soils used for vegetable farming were predominantly sandy (90.13%), providing good tillage properties but low water retention capacity. Clayey soils, although less frequent (8.52%), were present in significant proportions in certain zones. Gravelly substrates were nearly absent (1.35%). Regarding land-use history, 71.30% of vegetable plots were established on land with previous agricultural occupation (Table 3). Conversely, 28.70% of the plots were developed on lands originally designated as forest areas.

Table 3. Characteristics of the visited vegetable farming plots.

Variables	Modalities	Agroecological zones (AEZ)						Overall Mean
		AEZ I	AEZ II	AEZ III	AEZ IV	AEZ V	AEZ VI	
Cultivated area (m ²)	50-500	8.16	2.78	47.83	44.12	22.45	12.50	20.63
	501-2500	26.53	25.00	30.43	29.41	44.90	31.25	31.84
	2501-5000	34.69	61.11	21.74	26.47	20.41	25.00	31.84
	5001-10000	24.49	11.11	0.00	0.00	12.24	12.50	11.66
	> 10000	6.12	0.00	0.00	0.00	0.00	18.75	4.04
Soil type	Floodplain	71.43	66.67	100.00	44.12	40.82	25.00	56.05
	Well-drained land	26.53	33.33	0.00	17.65	59.18	75.00	37.67
	Streamside margin	2.04	0.00	0.00	38.24	0.00	0.00	6.28
Soil texture	Clay-dominated	4.08	22.22	26.09	0.00	0.00	9.38	8.52
	Gravelly	2.04	0.00	0.00	0.00	0.00	6.25	1.35
	Sand-dominated	93.88	77.78	73.91	100.00	100.00	84.38	90.13
Plot condition	Exploited	63.27	50.00	56.52	85.29	77.55	93.75	71.30
	New	36.73	50.00	43.48	14.71	22.45	6.25	28.70

3.1.4. Water Supply Modalities for Vegetable Crops

The analysis of water supply modalities for vegetable crops revealed two main sources: rainfall and artificial irrigation (Table 4). Natural water supply through precipitation was predominant during the rainy season, as reported by 78.91% of the surveyed farmers. During the dry season, irrigation became essential to maintain the soil moisture required for crop growth. The irrigation techniques employed varied according to the level of professionalization among the farmers. Manual irrigation, primarily carried out using watering cans, was the most commonly used method (54.26%). In contrast, drip irrigation systems although more efficient in

water management were rarely adopted (4.93%) due to their cost or technical requirements. Seasonality significantly influenced the water management practices. During the rainy season, rainfall constituted the main water source (78.91%), whereas in the dry season, manual irrigation became predominant (89.47%). Regarding the origin of the irrigation water, the data indicated a predominance of wells specifically constructed for this purpose (53.70%). Other farmers relied on natural sources such as nearby streams or accessible groundwater (Figure 1). The location of the water points varied with topographic configurations: some were situated downstream of the cultivated beds (71.30%), while others were located upstream on elevated edges (Figure 2).

Table 4. Irrigation practices for plants in vegetable production systems.

Irrigation supply methods	Growing seasons		Overall average
	Rainy season (n = 128)	Dry season (n = 95)	
Drip irrigation	0.78	10.52	4.93
Manual irrigation	28.12	89.47	54.26
rain-fed	78.91	13.69	51.12

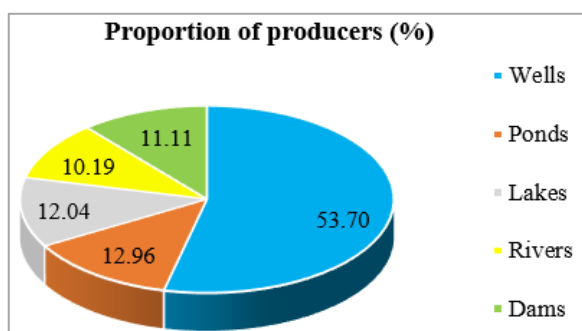


Figure 1. Distribution of producers according to the different water sources used for irrigation.

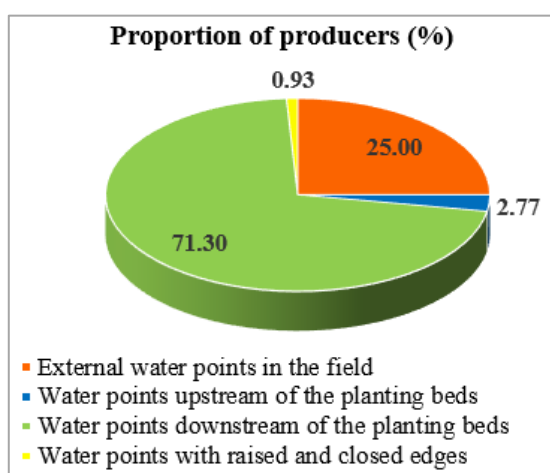


Figure 2. Distribution of producers according to the relative location of irrigation water sources in relation to the cultivation beds.

3.1.5. Endogenous Perception and Knowledge of Southern Blight by Producers

(i). Farmers' Level of Knowledge on White Rot

The analysis of data from the semi-structured interviews allowed the classification of vegetable crop producers into two main categories based on their level of knowledge of southern blight (or white rot). This distinction was made according to their visual recognition of the disease from images illustrating the characteristic symptoms on vegetable crops. Thus, 52.91% of the surveyed producers stated that they recognized the disease after observing the images. Conversely, 47.09% of the producers reported never having observed or identified this pathology in their fields. The geographic distribution of disease knowledge revealed significant disparities among the different agro-ecological zones (AEZs). In AEZs I, II, and IV, a relative majority of producers, 61.22%, 63.89%, and 70.59%, demonstrated the ability to identify the disease (Figure 3). In contrast, in AEZs III and VI, the proportion of producers who recognized the disease was markedly lower, at 39.13% and 21.88%, respectively (Figure 3). AEZ V presented an intermediate situation, with a recognition rate close to 50%.

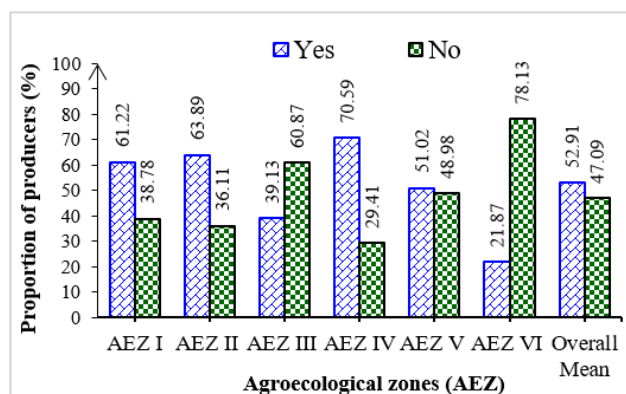


Figure 3. Distribution of producers according to their perception and knowledge of white rot.

(ii). Origin of Farmers' Knowledge on Disease Presence

The data analysis revealed that farmers' knowledge regarding the presence of the disease (Southern blight) originated from various information sources, including informal exchanges with other farmers, observations made during visits to neighboring plots, participation in agricultural training sessions, as well as direct observation in their own fields. Among these different modes of knowledge acquisition, direct observation in personal farms was the main source reported, accounting for 46.19% of responses (Figure 4). Furthermore, a significant proportion of vegetable crop producers (43.06%) indicated having no prior information about this disease (Figure 4).

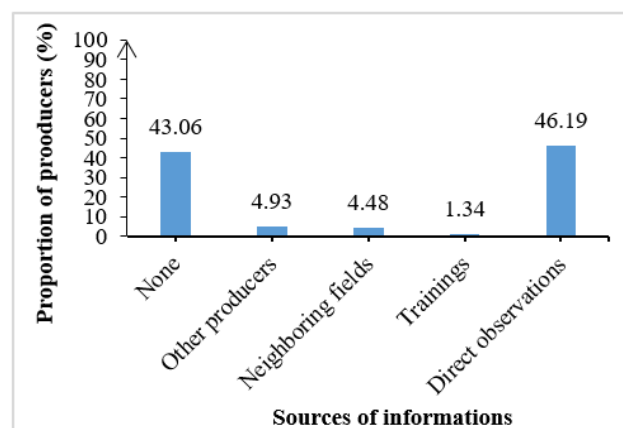


Figure 4. Distribution of growers according to sources of information about the disease.

(iii). Level of Knowledge of the Characteristic Symptoms of Southern Blight

The analysis of data regarding the knowledge of typical symptoms of southern blight (white rot) reveals marked heterogeneity, with significant variations according to agro-ecological zones (AEZs). The symptoms most fre-

quently and confidently identified by the producers were leaf yellowing, wilting of aerial parts, and plant drying. These visual manifestations were recognized by 37.67%, 42.60%, and 39.46% of producers, respectively, across all AEZs (Table 5). Conversely, the recognition of the role of soilborne fungi in leaf drop was limited. Approximately 39.94% of the respondents reported that the disease appeared as sporadic foci within the plots. The ability to identify specific diagnostic signs of southern blight, such as the presence of white cottony

mycelium and sclerotia, remained very low. Indeed, only 17.94% of producers associated the appearance of the mycelium with disease symptoms, while 8.52% recognized sclerotia as structures for pathogen dissemination and survival (Table 5). It is noteworthy that the majority of producers' knowledge appeared to be derived from direct observation of symptoms on their own crops, as evidenced by the 30.94% who attributed their knowledge to personal experience of the disease in the field.

Table 5. Growers' level of knowledge of the phytopathological symptoms of white rot due to *Sclerotium rolfsii*.

Types of symptoms	Agroecological zones (AEZ) with proportions of producers (%)						Overall mean
	AEZ I	AEZ II	AEZ III	AEZ IV	AEZ V	AEZ VI	
Yellowing	34.69	38.89	26.09	64.71	44.90	9.38	37.67
Wilt	48.98	44.44	30.43	58.82	46.94	15.63	42.60
Leaf worming	6.12	0.00	8.70	29.41	0.00	0.00	6.73
Withering	44.90	44.44	21.74	58.82	36.73	21.88	39.46
Scattered outbreaks	36.73	30.56	8.70	52.94	32.65	12.50	30.94
Mycelium	10.20	22.22	4.35	44.12	20.41	3.13	17.94
Sclerotia	0.00	5.56	0.00	32.35	10.20	3.13	8.52

(iv). Visual Detection Capacity of Disease Symptoms by Producers

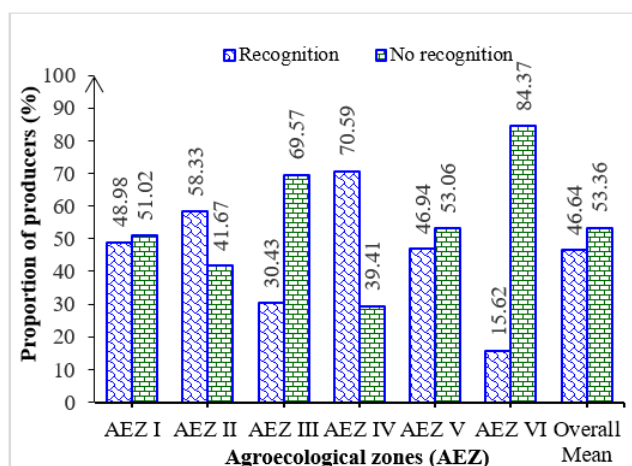


Figure 5. Growers' ability to diagnose the disease in situ during phytosanitary surveys.

During field visits, it was observed that 46.64% of producers were able to correctly identify symptomatic plants of the target disease, despite the simultaneous presence of other

plant pathologies. Conversely, nearly 50% of producers either confused the disease with other conditions or demonstrated an inability to precisely locate the infected plants. This ability to recognize symptoms varied significantly according to the agro-ecological zones (AEZ). Producers in AEZ IV exhibited a remarkable detection capacity, with a recognition rate of 70.59% (Figure 5). In AEZs I and V, approximately half of the producers correctly identified the diseased plants, whereas in AEZ II, this proportion was slightly above 50%. In contrast, markedly lower performance was recorded in AEZs III and VI, where only 30.43% and 15.63% of producers, respectively, were able to identify the specific disease symptoms (Figure 5).

(v). Mycological Identity of the Pathogen's Proliferative Structures

The dissemination structures of the fungal pathogen remain largely unknown among producers. Indeed, only 13% of them recognized the mycelium and sclerotia as structures belonging to a fungal microorganism (Figure 6). This perception is generally consistent across all agro-ecological zones (AEZs), with the exception of AEZ IV, where a significantly higher proportion (41.18%) of producers correctly identified these structures as soil-borne fungi (Figure 6).

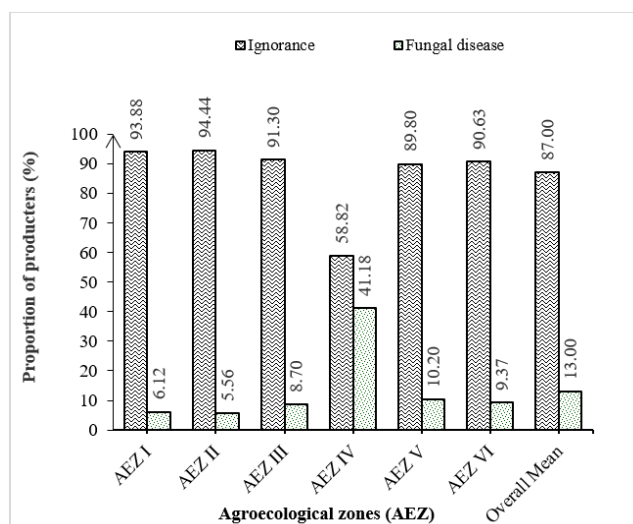


Figure 6. Distribution of growers according to their level of knowledge of the etiology of pathogen proliferation structures.

(vi). Perception of the Host Plant Species Susceptible to White Rot

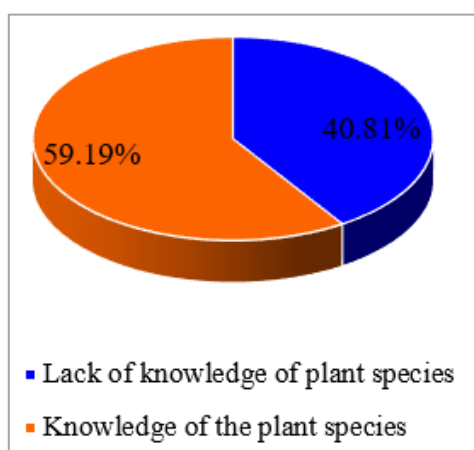


Figure 7. Distribution of growers according to their level of knowledge of plant species susceptible to the disease.

Out of a sample of 223 surveyed farmers, only 132 (59.19%) were able to identify at least one plant species they considered susceptible to white rot, while 91 producers (40.81%) had no knowledge of any susceptible species

(Figure 7). Plant species belonging to the Solanaceae family, particularly *Solanum lycopersicum* (Tomato), were most frequently cited (58.52%) as particularly vulnerable to infection by *Sclerotium rolfsii* (Figure 8). In contrast, leguminous crops such as *Arachis hypogaea* (Peanut) and *Phaseolus vulgaris* (Common bean), as well as other vegetable species like *Lactuca sativa* (Lettuce), *Brassica oleracea* (Cabbage), and *Abelmoschus esculentus* (Okra), were rarely mentioned (Figure 8).

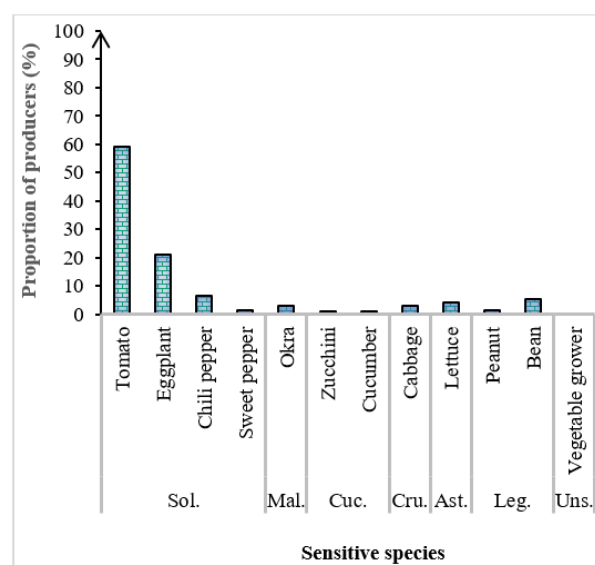


Figure 8. Farmers' perception of crop susceptibility to white rot caused by *Sclerotium rolfsii*.

Sol. = Solanaceae, Mal. = Malvaceae, Cuc. = Cucurbitaceae, Cru. = Crucifer, Ast. = Asteraceae, Leg. = Leguminosae, Uns. = Unspecified

(vii). Perceived Timeline of White Rot Emergence

Analysis of data from 223 farmers revealed that only 115 individuals (51.57%) were able to indicate the periods during which white rot appeared (Table 6), while 108 producers (48.43%) provided no information on this matter. Among those who responded, the fruiting stage (47.98%) and the rainy season (50.22%) were the most frequently cited periods associated with the emergence of the disease. Phenological stages such as the vegetative phase and flowering were rarely mentioned (5.38% and 8.07%, respectively).

Table 6. Chronology of onset of white rot due to *Sclerotium rolfsii* reported by growers.

Variables	Effectif (N=223)	Proportion of producers (%)
Knowledge	Yes	115
	No	108
Phenological stages	Vegetative	12
		5.38

Variables		Effectif (N=223)	Proportion of producers (%)
Growing season	Flowering	18	8.07
	Fructification	107	47.98
	Rainy season	112	50.22
	Dry season	26	11.66
	Hot season	9	4.04

3.1.6. Producers' Knowledge Level of White Rot

The assessment of producers' knowledge level regarding white rot caused by *S. rolfsii* was conducted using a scoring system based on their responses to a targeted questionnaire. This methodology enabled the classification of producers into three distinct categories: low, moderate, and good knowledge of the disease.

(i). Influence of Agro-ecological Zones on Knowledge Level

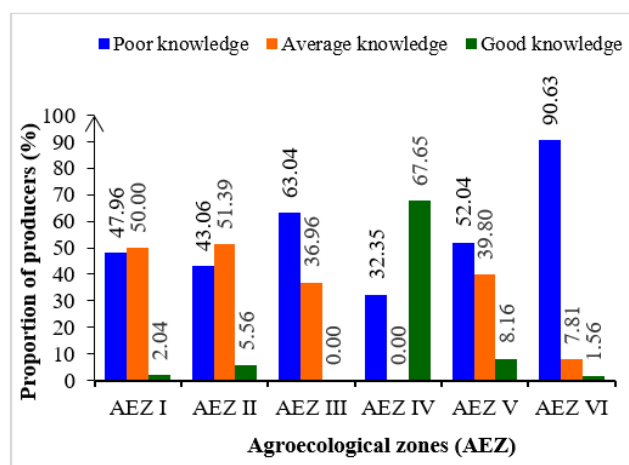


Figure 9. Distribution of levels of knowledge of southern blight (white rot) according to the agro-ecological zones studied.

Analysis of the relationship between agro-ecological zones (AEZs) and knowledge level revealed a statistically significant association (Chi-square test, $p < 0.05$), indicating that geographic location substantially influences producers' understanding of the disease. The association coefficients showed a moderate to strong relationship, confirming this influence (Figure 9). In particular, AEZ IV stood out with a notable proportion of producers exhibiting good knowledge of white rot. In contrast, AEZ I and II showed a mixed profile, with an even distribution between moderate knowledge and lack of awareness of the disease. The situation was more concerning in AEZs III and VI, where 63.04% and 90.63% of

producers reported being unaware of the existence of this fungal disease (Figure 9).

(ii). Gender Influence on Knowledge Level

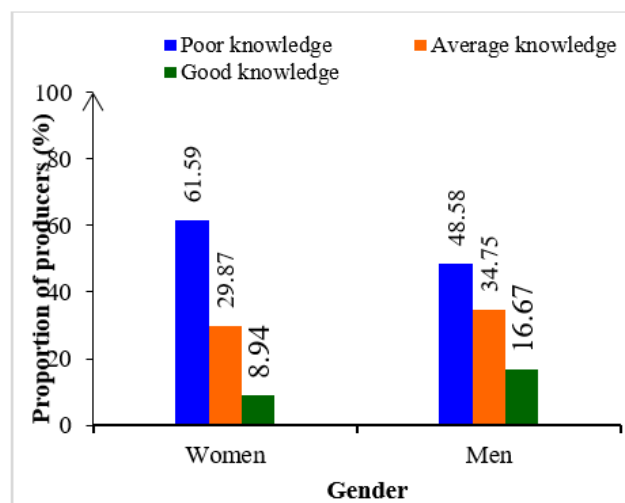


Figure 10. Influence of gender on the phytopathological knowledge of white rot in vegetable.

The Chi-square test of independence applied to the variable "gender" revealed a statistically significant relationship with the level of knowledge ($p < 0.05$). However, the association coefficients indicated a weak relationship. Overall, men exhibited a slightly higher level of knowledge than women. Specifically, 16.67% of men versus 8.54% of women demonstrated good knowledge of white rot disease (Figure 10). Nevertheless, the majority of both groups showed low to moderate levels of knowledge, with a higher prevalence of low knowledge levels among women.

(iii). Impact of Level of Education on Knowledge of White Rot

The level of education is a significant determinant of the growers' knowledge of white rot. Statistical analysis showed a positive correlation between higher educational attainment and the probability of acquiring appropriate knowledge of this fungal pathology. Growers with secondary education or

higher had the highest proportions of good knowledge of the disease, estimated at 28.57% and 25%, respectively (Figure 11). On the other hand, a relative majority of growers with higher education (62.50%) had a level of knowledge considered average. Conversely, unschooled growers and those with only primary education had high proportions of poor knowledge (56.97 and 54.55% respectively), accompanied by very low rates of good knowledge (11.52 and 6.82%).

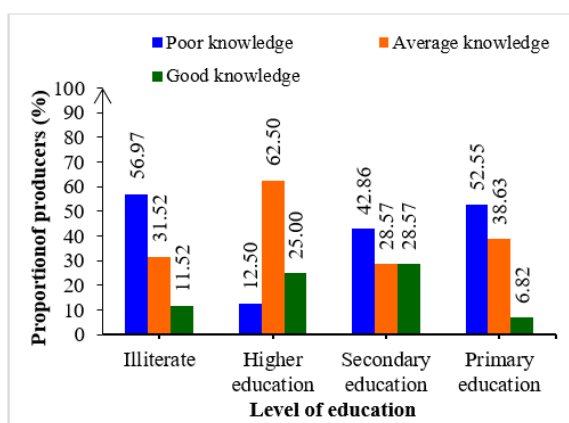


Figure 11. Correlation between growers' level of education and their knowledge of white rot.

3.2. Cultural Practices and Farmers' Strategies for Southern Blight Management

3.2.1. Crop Rotation Strategies

Analysis of farming practices revealed that 26.91% of growers have established their plots on former forest land (Figure 12). However, 36.10% of growers implemented risky rotations, characterized by the renewal of species from the same botanical family or the same crop (Figure 12). Conversely, a similar proportion (36.99%) adopted crop rotations that are more relevant from a phytosanitary point of view, by integrating species from other families, less sensitive or even tolerant to *Sclerotium rolfsii*.

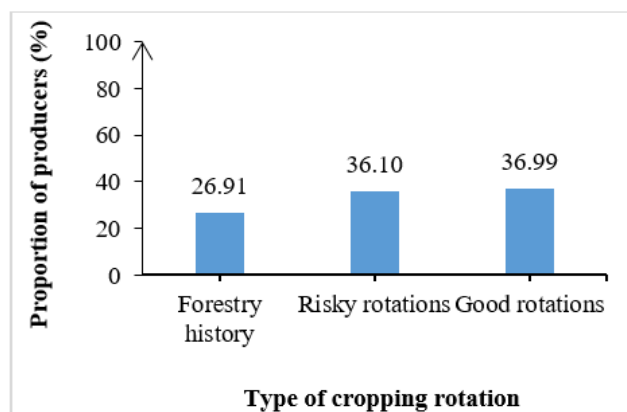


Figure 12. Crop rotation strategies used on farms.

3.2.2. Phytosanitary Treatments Applied to Plants

(i). Use of Fungicides

The survey revealed that 52.02% of growers do not apply any fungicide treatment, sometimes due to reluctance or unfamiliarity with chemical control practices (Table 7). On the other hand, 47.98% of growers use chemical fungicides, applied either with adapted equipment or empirically. The most frequently cited active substances were azoxystrobin (Callicuivre) at 27.35%, the chlorothalonil + carbendazim mixture (Banko Plus 660 SC) at 14.80%, and maneb at 8.97% (Table 7). The majority of treatments were applied as a curative response as soon as symptoms appeared (49.77%), whereas preventive control was marginal (4.48%). Although 44.39% of the growers adhered to registered doses, 41.25% of the growers reported adjusting doses according to symptom severity, and 26.45% went so far as to double doses in the event of severe infestation, in defiance of agronomic recommendations (Table 7).

Table 7. Main fungicides used by growers to manage fungal diseases in vegetable crops and frequency of use.

Variables	Application des fungicides	Active substances	Proportion (%)
Application	Yes	-	47.98
	No	-	52.02
Fungicide applications	Banko Plus-Maneb	Chlorothalonil (550 g/l) et carbendazine (110 g/l)	3.14
	Callicuivre - Mancotop	Azoxystrobin (75 g/l) - Mancozeb 800 g/kg	3.14
	Callicuivre-Maneb	Azoxystrobin (75 g/l)- Maneb	0.45
	Callicuivre - Maneb	Azoxystrobin (75 g/l)- Maneb	0.45

Variables	Application des fongicides	Active substances	Proportion (%)
Fungicide application times	Banko Plus	Chlorothalonil (550 g/l) et carbendazin (110 g/l)	14.8
	Callicuivre	Azoxystrobin (75 g/l)	27.35
	Poudre du Ghana	Inknown	0.45
	Fongicide cacao	Inknown	0.45
	Mancotop 80 W	Mancozeb 800 g/kg	5.38
	Man ðe	Maneb	8.97
	Fongicide maraicher	Inknown	1.35
	Nom inconnu	Inknown	1.35
	Avant apparition des sympt ðmes	-	4.48
Application dose	Apr ès apparition des sympt ðmes	-	49.77
	Dose homologu ée	-	44.39
	Deux fois la dose homologu ée	-	26.45
	En fonction de l'intensit é des sympt ðmes	-	41.25
	Sans mesure	-	4.03
Application materials	Pulv érisateur	-	43.50
	Applicateur traditionnel adapt é	-	2.69
	Arrosoir	-	4.03

(ii). Farmers' Prophylactic Methods for Disease Management

With regard to prophylaxis, 22.42% of growers said they uprooted diseased plants without thermal destruction, while 68.16% practiced ridging in the hope of vegetative recovery

(Table 8). Reducing inter-plant spacing was practiced by 80.72% of the growers, contributing to high plant density. In addition, all growers declared that they left crop residues on the surface (100%).

Table 8. Prophylactic practices applied by growers in relation to disease management.

Prophylactic measures		Proportion of producers (%)
Managing diseased plants	Removal of diseased plants	22.42
	Ridging around plants	68.16
	Field abandonment	0.22
Planting density	Dense (no line spacing)	80.72
	Not very dense (respecting line spacing)	18.83
	Very dense (no line spacing)	0.45
Weed management	Weekly	68.61
	According to availability	6.28
	Monthly	25.11
Harvest residues	Not incorporated	100

(iii). Organic Fertilizers and Soil Improvers

Mineral fertilizers were used by 61.88% of the growers, with 38.34% favoring NPK formulas and 5.83% urea 46% (Table 9). Applications of foliar fertilizers (Callifert, Fertigofol) were rare (8.30%). Other formulations such as starter phosphates and

calcium nitrate were poorly represented. Note that 11.21% of the growers did not know the products they used. Organic amendment was used by 29.60% of the growers, with inputs in the form of manure (14.80%) or plant residues (14.80%), applied as soil cover, in patches or as a foliar solution.

Table 9. Fertilizers provided by growers.

Variables	Fertilizer application	Number	Proportion of producers (%)
Mineral fertilizer use	Yes	138	61.88
	No	85	38.12
	NPK	86	38.56
	Urea	13	5.83
	Biological fertilizers (technokel, supergrow, black fertilizer, biofertilizer)	5	2.24
Type of mineral fertilizer	Starter fertilizers	1	0.45
	Foliar fertilizers (callifert, fertigofol)	18	8.07
	Unknown	25	11.21
	Calcium nitrate	3	1.35
	Pectofauna	2	0.90
Organic fertilizer	Yes	66	29.60
	No	157	70.40
Types of organic fertilizers	Manure	33	14.80
	Crop residues (coconut husk, corn bran, wood chips)	33	14.80

3.3. Geographic Distribution and Incidence of Southern Blight in the Different Agro-ecological Zones of Côte d'Ivoire

3.3.1. Diversity of Affected Crops and Field Infection Rates

As part of the phytopathological survey conducted across 223 vegetable plots, 144 of them, representing 64.57%, exhibited typical symptoms of southern blight (Table 10). These symptoms included the presence of sclerotia and white cottony mycelium localized at the collar region of the plants or on the soil surface. Analysis of the affected crops revealed a marked predominance of the disease among the Solanaceae family, particularly tomato (*Solanum lycopersicum*), which accounted for 65.28% of the recorded cases (94 infected plots).

This crop thus constitutes the main host affected by *Sclerotium rolfsii*. Other vegetable species were also affected although to a significantly lesser extent. The highest prevalences after tomato were observed in eggplant (*Solanum melongena*): 9.03% (13 plots), peanut (*Arachis hypogaea*): 6.94% (10 plots), and common bean (*Phaseolus vulgaris*): 5.56% (8 plots). Species less frequently affected, with an incidence below 3%, included parsley (*Petroselinum crispum*): 2.78% (4 plots), cabbage (*Brassica oleracea*): 2.08% (3 plots), zucchini (*Cucurbita pepo*), lettuce (*Lactuca sativa*), and sweet pepper (*Capsicum annuum*): each with 1.39% (2 plots). Finally, carrot (*Daucus carota*), cucumber (*Cucumis sativus*), okra (*Abelmoschus esculentus*), onion (*Allium cepa*), sweet potato (*Ipomoea batatas*), and chili pepper (*Capsicum* spp.) were the least represented, with only one affected plot each, corresponding to 0.69% (Table 10).

Table 10. Prevalence of southern blight according to vegetable species identified during the phytopathological survey in Côte d'Ivoire.

Family	Species	Variety	Number of fields encountered	Number of infected fields	Proportions (%)
Amaralldaceae	Onion	Violet	1	1	0.69
Apiaceae	Carrot	Royal cross,	1	1	0.69
	Parsley	Fris ée, Unknown	4	4	2.78
Asteraceae	Lettuce	Fris ée, Unknown, Mineto,	5	2	1.39
Brassicaceae	Cabbage	F1 Tropicana, kkcross, Royal cross, Tropica cross F1	11	3	2.08
Convolvulaceae	Potato	Leaf	1	1	0.69
Cucurbitaceae	Cucumber	Poinsett	6	1	0.69
	Zucchini	Unknown, Koubera, Raffia palm	6	2	1.39
Leguminosae	Peanut	Early	12	10	6.94
	Bean	Burkina, Cora, Unknown	7	8	5.56
Malvaceae	Jute mallow	Unknown	3	0	0.00
	Okra	Clemson, Hir é Kirikou F1, local	3	1	0.69
Poaceae	Maize	Unknown	1	0	0.00
Polygonaceae	Sorrel	Unknown	2	0	0.00
Solanaceae	Eggplant	Bello, Djemba, Kalenda, Kotobi, Local, Local bokouma, Local Koromgbo, local N'drowa, F1 Egg, violet	34	13	9.03
	Pepper	Big sun, Unknown, local, Long-fruited local	7	1	0.69
	Sweet pepper	Improved, Tibesti, Yellow Wonder	2	2	1.39
	Tomato	F1 Caviar, F1 Cobra 26, Unknown, Jarra, Local, Mona F1, Padma, Petomech, PV, Raja, Riogrand, Tropimech, UC 82 B	141	94	65.28
Grand total			223	144	

3.3.2. Symptomatology of Southern Blight

(i). Decay Symptoms

Infected plant tissues showed changes characteristic of southern blight, marked by progressive necrosis beginning at the crown. This necrosis manifested itself as a browning of the tissue, followed by gradual desiccation extending longitudinally toward the base of the stem. At an advanced stage of infection, external colonization by a white cottony mycelium, typical of *S. rolfii*, was frequently observed, accompanied by the formation of irregularly shaped, brownish to black sclerotia on the surface of the necrotic tissue. In *Lactuca sativa* (Lettuce), a noticeable reduction in vegetative vigor was recorded upstream of the expression of visible symptoms. However, macroscopic fungal signs were rarely detected

inside the sectioned stems (Figure 13).

(ii). Symptoms of Wilting and Yellowing

Early symptoms observed on infested plants mainly manifested themselves as progressive leaf collapse, often accompanied by yellowing of the basal leaves. In some particularly susceptible plant species, such as *Abelmoschus esculentus* (Okra), additional manifestations were noted, notably leaf browning beginning at the margins and extending toward the leaf blade (Figure 13).

(iii). Symptoms of Terminal Desiccation

Vegetative tissue desiccation was observed along a basipetal-apical gradient (from basal leaves to apex). Immature fruits, although wilted, generally remained attached to the necrotic plant (Figure 13).



a: bean; b: peanut; c: zucchini; d et j: cucumber; e et f: lettuce; g: carrot; h: tomato; i: cabbage; k: onion; l: eggplant

Figure 13. Various characteristic symptoms of southern blight on different crops.

3.3.3. Epidemiology of the Disease in Terms of Incidence and Severity

(i). Variability by Agro-ecological Zone

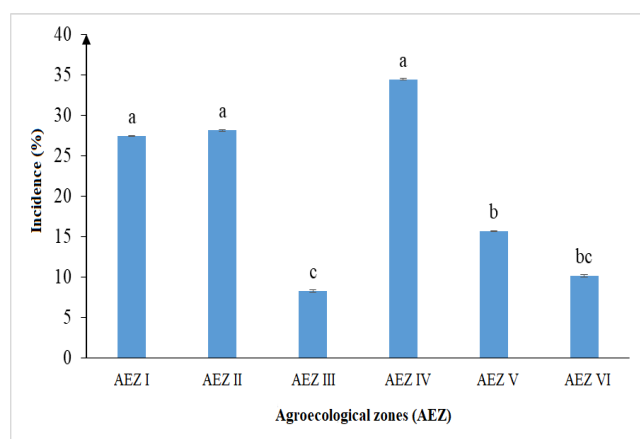


Figure 14. Incidence of southern blight according to agroecological zones (AEZ).

The average incidence of southern blight ranged from 8.25 to 34.44%. Analysis of variance with one classification criterion showed a statistical difference between agro-ecological zones ($p < 0.0001$). Duncan's test at the 0.05% threshold showed three (3) homogeneous groups. AEZ I, II and IV formed the group of zones with the highest incidence, with

values of 27.39, 28.11 and 34.44%, respectively. AEZ IV recorded the highest incidence. AEZ III recorded the lowest incidence (8.25%). Finally, AEZ V and VI formed the intermediate group, with incidence values of 15.63 and 10.11%, respectively (Figure 14). Severity, which expressed the severity of the disease according to the scores chosen, ranged from 3.29% to 22.59%. A significant difference was observed between AEZs ($p < 0.0001$). The highest severity was observed in AEZ IV (Figure 15). Duncan's test classified the ZAEs from highest to lowest severity in the order AEZ IV (22.59%), AEZ I (28.11%), AEZ II (14.24%), AEZ V (11.47%), AEZ VI (7.17%) and AEZ III (3.29%).

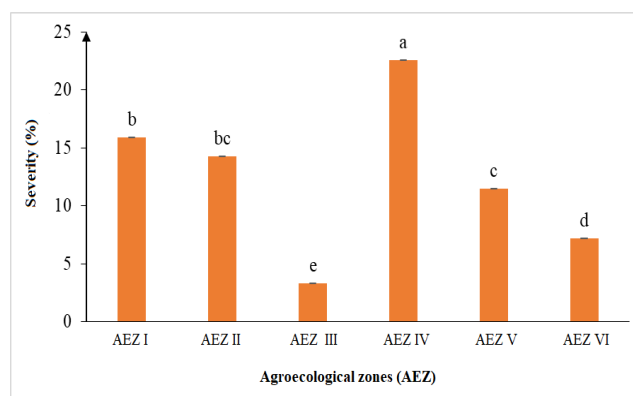


Figure 15. Severity of southern blight according to agroecological zones (AEZ).

(ii). Regional Variability

White rot was detected in all 18 regions explored. Marked disparities were observed within the same AEZ (Table 11). The highest incidences were recorded in the Grands-Ponts (65.17%), Iffou (47.54%), Moronou (34.60%), Marahou é (34.02%), and Nawa (33.90%) regions. The highest levels of severity were recorded in Grands-Ponts (34.34%) and Iffou (32.98%).

Table 11. Incidence and severity of southern blight by region.

Regions	Incidence (%)	Severity (%)
Agneby Tiassa	8.75 ± 0.27 e	4.08 ± 0.08 d
Goh	14.49 ± 0.49 d	20.68 ± 0.14 b
Ind énie Djuablin	17.69 ± 0.44 d	9.895 ± 0.13 c
Les grands ponts	65.17 ± 0.220 a	34.34 ± 0.07 a
Loh Djiboua	19.25 ± 0.37 c	11.96 ± 0.11 c
Haut Sassandra	23.37 ± 0.21 c	12.09 ± 0.06 c
Marahou é	34.02 ± 0.44 ab	20.93 ± 0.13 b
Nawa	33.90 ± 0.55 ab	12.41 ± 0.16 bc
Guemon	9.67 ± 0.20 e	3.56 ± 0.06 d
Tonkpi	6.00 ± 0.34 f	2.83 ± 0.09 d
B érier	26.83 ± 0.24 cd	18.82 ± 0.07 b
Moronou	34.60 ± 0.44 ab	19.00 ± 0.13 b
Iffou	47.54 ± 0.40 b	32.98 ± 0.12 a
B éré	7.29 ± 0.44 f	10.21 ± 0.13 c
Gb éké	24.75 ± 0.16 c	14.27 ± 0.05 bc
Worodougou	12.34 ± 0.12 cd	9.92 ± 0.04 c
Poro	19.07 ± 0.20 c	12.18 ± 0.06 c
Tchologo	2.46 ± 0.26 g	2.55 ± 0.08 d
Probability (p)	p < 0.0001	p < 0.0001

4. Discussion

The proportions of market gardeners recorded across the various agro-ecological zones reveal a strong enthusiasm for this activity, both in the rural and urban areas of Côte d'Ivoire. The sociodemographic analysis highlights the diversity of producer profiles, with a marked male predominance in most zones. This trend, as reported by Ake *et al.* [18], is attributed to the physically demanding nature of agricultural work. Nevertheless, some notable exceptions exist. In Agro-ecological Zone (AEZ) III, vegetable production is carried out exclusively by women, aligning with observations by Kouam é *et al.* [19] in Ahou é and Ball é [20] in Korhogo,

who underscored the significant involvement of women in subsistence-oriented horticulture. Although numerically underrepresented, women are actively engaged in this sector, with tangible impacts on their empowerment. Indeed, N'Goran [21] demonstrated that 67.37% of women involved in market gardening reported managing their own income, compared to only 37.07% among those not engaged in the sector. The predominance of individuals aged 26 to 55 years reflects the dynamism of the sector and its appeal to the economically active population. This observation is corroborated by Wognin *et al.* [22], who reported that 65.7% of vegetable producers in Abidjan were between 25 and 35 years old. The high proportion of married individuals may reflect the burden of family responsibilities as a motivational factor for engagement in production. However, the low level of formal education (72.65% illiteracy rate) represents a major barrier to the adoption of modern farming practices and rational pathogen management, as emphasized by Ake *et al.* (2023). Regarding landholdings, the wide range of cultivated areas (50 to 5000 m² in most cases) reflects diversified production objectives. These findings are consistent with those of Dosso *et al.* [23], who noted a predominance of plots under 1 ha in Côte d'Ivoire. Smaller plots are generally geared toward self-consumption, whereas larger farms supply local or urban markets through commercial networks. The scarcity of farms exceeding 1 ha reflects structural constraints, particularly land tenure issues and limited access to agricultural inputs and equipment. The widespread use of lowland areas in AEZs I to IV reflects a search for favorable water conditions. However, these humid environments also promote the development of soilborne pathogens such as *S. rolf sii*. Conversely, in AEZ VI, vegetable production is mostly conducted on upland soils, while the lowlands are reserved for staple crops. The dominance of sandy soils facilitates tillage but complicates water and nutrient management, posing a major challenge for sustainable production. The epidemiological survey revealed a concerning prevalence of southern blight caused by *S. rolf sii*, affecting 64.57% of the sampled plots. Considerable disparities exist between agro-ecological zones: AEZs I, II, and IV exhibit the highest incidence rates (27.39%, 28.11%, and 34.44%, respectively), with a maximum disease severity of 22.59% observed in AEZ IV. These findings are consistent with those of Bolou *et al.* [10], although the latter reported a higher incidence of AEZ I. At the regional level, the most affected areas included Grands-Ponts (65.17%), Iffou (47.54%), Moronou (34.60%), Marahou é (34.02%), and Nawa (33.90%). This spatial variability is largely influenced by region-specific agroclimatic conditions (humidity, temperature, and soil texture), as suggested by Punja [24] and Kakela *et al.* [25]. For example, the proximity to water bodies in AEZ IV (38.24% of plots) creates a microclimate conducive to the proliferation of *S. rolf sii*. The pathogen's host range indicates high polyphagy, affecting many vegetable crops, with a marked predominance in Solanaceae, particularly tomato (65.28%). This observation aligns with the findings of Bolou *et*

al. [10]. The spatial distribution of the pathogen is shaped by a combination of factors, including pedological characteristics, cropping history, irrigation systems, plant diversity, and seasonality. Certain cultural practices, especially the reduction of inter-row spacing (80.72% of producers), contribute to the creation of moist microclimates. The systematic retention of crop residues on the soil surface further exacerbates the risk, as these residues harbor sclerotia the fungus's survival structures—which can persist in the soil for several years [26]. The dominance of sandy soils (90.13%) in vegetable-growing areas necessitates frequent irrigation to maintain adequate moisture. The prevalent use of watering cans (54.26%) may lead to splash dispersal of the pathogen. Moreover, the downstream location of water sources (71.3%) increases the risk of pathogen spread via runoff. Farmers' perceptions agree with these findings. The fruiting stages (47.98%) and the rainy season (50.22%) were perceived as critical periods for disease onset. This supports prior research indicating that high humidity and physiological stress during the reproductive stages favor sclerotial germination and mycelial growth. However, producers' knowledge of the disease remains limited. Only 52.91% could visually recognize the symptoms. In AEZs III and VI, where disease incidence is low, recognition rates are also low, suggesting that direct experience plays a crucial role in learning. Visual observation (46.19%) is the primary source of knowledge, but it has limitations. Farmers can identify certain symptoms (wilting: 42.60%; yellowing: 37.67%; desiccation: 39.46%), but with a high illiteracy rate (72.65%), their understanding of the pathogen's life cycle remains minimal. Only 13% could identify fungal structures, reflecting a low diagnostic capacity and frequent confusion with inert debris. The lack of phytosanitary training results in limited implementation of preventive measures. Despite the widespread practice of earthing-up (68.16%), the elimination of infection sources is rare, and fungicide use is often inappropriate (52.02% of cases), contrary to the recommendations of Sikirou *et al.* [27]. Furthermore, the frequent repetition of susceptible crops (36.10%) worsens disease severity, as demonstrated by Bolou *et al.* [10]. These findings are consistent with the analyses of Tittonell & Giller [15] and Omer *et al.* [12], who emphasized that limited cognitive and technical capital is a structural driver of phytosanitary vulnerability. This study thus underscores the need for an integrated approach to the sustainable management of southern blight. Such an approach should incorporate participatory surveillance tools, early diagnosis, strategic crop rotations, the use of bio-inputs, and the valorization of indigenous knowledge systems within an agro-ecological framework, as advocated by Srivastava [28] and Gullino *et al.* [14]. This transdisciplinary approach is essential for enhancing the resilience of Ivorian vegetable agroecosystems against soilborne pathogens.

5. Conclusion

This study highlights the epidemiological and socio-technical complexity of southern blight in vegetable

farming systems in Côte d'Ivoire, revealing a high prevalence (64.57%) and alarming levels of severity, particularly in Agro-Ecological Zone IV. Cross-analysis of the data underscores the multifactorial interactions among edaphic conditions, cropping practices, educational levels, and climatic dynamics that shape the distribution of the pathogen *S. rolfsii*. The pronounced lack of farmers' knowledge such as the inability to recognize characteristic symptoms of the disease and widespread structural illiteracy (72.65%) constitute major barriers to early detection and the implementation of effective prophylactic strategies. The empirical use of fungicides, inappropriate crop rotations, failure to eliminate infection foci, and poor knowledge of diagnostic fungal structures further intensify the vulnerability of vegetable agroecosystems to the disease. In response to these systemic weaknesses, an integrated approach is essential—one that combines local capacity building, co-development of solutions with farmers, integration of biopesticides, and optimization of crop rotation practices. This agro-ecological paradigm, both inclusive and resilient, emerges as a promising pathway to contain southern blight while enhancing the phytosanitary sustainability of vegetable farming systems in Côte d'Ivoire during the ongoing agro-ecological transition.

Abbreviations

AEZ	Agroecological Zone
ANOVA	Analysis of Variance
GPS	Global Positioning System
p	Probability

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Author Contributions

All authors contributed substantially to the study's design, experimental implementation, and technical execution. They collaboratively conducted data analysis, interpreted the results, and participated in the structured writing and critical revision of the manuscript. All authors have read, approved, and fully endorse the final version.

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Data Availability Statement

The author's state that all data used in the preparation of this article can be made available by the corresponding author upon reasonable and justified request.

Conflicts of Interest

The authors declare no conflicts of interest.

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