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Association of apple powdery mildew (*Podosphaera leucotricha*) and anthracnose (*Neofabraea malicorticis*) epidemics with environmental factors and agronomic practices in Chencha highlands, southern Ethiopia

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Abstract

Apple powdery mildew and anthracnose are widely distributed and major constraints on apple production around the world. The objective of the study was to determine powdery mildew and anthracnose prevalence, intensity, and association between biophysical factors. To this effect, field assessments were conducted in Chencha highlands of southern Ethiopia during the 2021 and 2022 production years. A multistage random sampling approach was followed for data collection, and the association between disease severity and biophysical factors was analyzed using a logistic regression model. A total of 164 apple orchards were inspected in five of the top apple-producing farmer associations (FAs) in the district. Results showed that the diseases were prevalent in apple fields, although the level of importance varied among FAs. Mean powdery mildew and anthracnose severity were lower in 2021 (23.56 and 22.39%) than in 2022 (28.89 and 26.11%), respectively. Age of tree, cropping system, disease status and management, yield, and weed showed highly significant ($P < 0.0001$) associations with powdery mildew and anthracnose severity. Likewise, altitude, production year, survey site, and relative humidity were significantly ($P < 0.0001$–0.05) associated with anthracnose severity in both single and multiple reduced variable models. In the model, precipitation was highly significant ($P < 0.0001$) in association with powdery mildew severity than anthracnose. Aged trees, monocropping, disease, and weed management, along with favorable environmental conditions, were highly contributing factors to the high (> 26% for powdery mildew and > 24% for anthracnose) disease severity in the model. Conversely, recently established orchards (≤ 5 years), mixed crops with legumes, and pruning with appropriate sanitation applied as disease management practices contributed to low (< 26% for powdery mildew and < 24% for anthracnose) disease severity. In conclusion, the current study indicated that powdery mildew and anthracnose diseases were major constraints on apple production, and their epidemic development was significantly influenced by biophysical factors. Hence, the findings may provide a basis for developing powdery mildew and anthracnose sustainable management strategies, which would ensure apple production in the study areas

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and in agro-ecologies of a similar kind elsewhere. Thus, following intercropping and/or mixed cropping and proper disease and weed management, along with other good agronomic practices, is suggested to manage the two diseases in the area and other related agroecologies.

Keywords Agronomic practices, Apple orchards, Disease severity, Logistic regression model, Production constraints

Background

Apple (*Malus domestica* B.) is one of the most popular fruit crops growing in temperate regions of the world (FAOSTAT 2023). Globally, apples are the 3rd most important fruit crop, followed by bananas and grapes (FAOSTAT 2023). It is believed that apples originated in Asian countries, particularly Asia Minor and western China (Juniper et al. 1996). China and the United States of America (USA) are the leading apple-producing countries in the world (O'Rourke 2001). In Africa, apples are widely produced in Egypt, Kenya, Morocco, and South Africa (Salele and Tsegaye 2020). Historically, in Ethiopia, apple fruit was first introduced in the nineteenth century in the areas of the Gamo highlands of southern Ethiopia (Girmay et al. 2014). Apple production is increasing gradually, from the first introduced areas of Chencha district to the whole highland area of the country. Currently, the government of Ethiopia has announced that farmers should plant apples and other tree fruits on the common lands and home gardens to achieve the green legacy and 20 × 40 policies of the country. According to the zone agricultural bureau, in Gamo zone, apple fruits covered a total area of about 7123.4 ha in 2022/23 with a total production of 142,468 tons, which was par higher than the previous coverage in 2020/21 production seasons of 5938.8 ha with a total production of 118,538.45 tons.

However, numerous diseases seriously challenge apple production in Ethiopia (Shega et al. 2023). Common diseases in apple orchards include powdery mildew, apple scab, anthracnose, root rot, fruit rot, leaf defoliation, blossom blight, trunk, and viral diseases (Grove et al. 2003; Besufkad et al. 2018). Apple powdery mildew caused by *Podosphaera leucotricha* and anthracnose caused by the fungus *Cryptosporiopsis curvispora* (Teleomorph *Neofabraea malicorticis*) are the most important threats to apple orchards in Ethiopia (Besufkad et al. 2018). However, there are other *Neofabraea* spp. (*N. alba* and *N. perennans*) responsible for anthracnose canker in orchards and storage worldwide (Saville 2015; Garton et al. 2018).

Apple powdery mildew affects leaves, shoots, blooms, buds, young branches, flowers, and fruits. The initial symptoms show silver-grey and gradual defoliation, stunted growth, and dieback, which results in final tree collapse and huge yield losses (Moinina et al. 2019). On the other hand, anthracnose causes severe yield losses through girdling stems and branches, which affects overall tree health and above-ground biomasses (Sharma 2015). Anthracnose infection starts when the first rain showers and the tree stems receive enough moisture (Levesque et al. 2001; Cameldi et al. 2016). In general, the identification of disease status and special distribution are the first and most important components of integrated disease management (Yoder 2000; Tian et al. 2021). It is an important tactic for time and correct management in the integrated disease management approach (Yoder 2000; Sulaiman et al. 2023). According to the Zone Agricultural Bureau, the productivity of apples varied from 18.5 tons/ha to 30 tons/ha. The yield variation is mainly due to the above-listed biotic factors. However, the current status and biophysical factors that contribute to the development of apple disease, including the age of fruits, fruit management systems, cropping system dynamics, cultural disease management practices, weed management, and other important factors, are not well documented in the study area. Baseline information on apple powdery mildew and anthracnose disease epidemics is a fundamental requirement for the development of management interventions in the study area. In this regard, Gudero and Terefe (2018) and Mengesha et al. (2023) reported that biophysical factors like cropping systems, inappropriate agronomic practices, and environmental factors significantly influence disease onset, epidemic development, and associated yield loss.

Understanding the relationship between disease prevalence, intensity, and biophysical factors would aid in identifying key variables and developing integrated and long-term control strategies (Mengesha et al. 2018; Yitayih et al. 2021). Previous reports indicated that the association of different biophysical factors and the status of disease development are also important measures to incorporate into further feasible management strategies (Mengesha et al. 2023; Terefe et al. 2023). Accordingly, to design efficient and effective management strategies that focus on the host, pathogen, environment, and their interactions, information on occurrence, prevalence, relative importance, and agronomic factors influencing apple powdery mildew and anthracnose disease epidemic development is urgently necessitated. Therefore, the objectives of this study were to determine the current status, prevalence, intensity, and relative importance of apple powdery mildew and anthracnose diseases and the association of environmental factors and agronomic practices influencing disease epidemics in Chencha highlands, southern Ethiopia.

Results

General characteristics of surveyed fields

Different agro-ecologies, farm management practices, land cover, cropping systems, enset forest in the garden, and undulating, slope-to-rugged mountains were the major characteristics of Chencha district. The surveyed orchards were located in an altitude range of 2590–2841 m above sea level (m.a.s.l). Among the inspected orchards, 30.49% and 69.51% of the orchards were located at < 2700 and ≥ 2700 m.a.s.l., respectively. The size of the orchards inspected in the district ranged from 0.03 to 1 ha in farmer's orchards and 0.5 to 3 ha for state farmers (Kalehiwot Church). In the district, over seventy apple varieties are cultivated, with an average of ten varieties per orchard. Chencha galla, Bonded Red (BR), Bartlett pear, Crispin, Jonagored, Red Delicious, Royal Galla, Golden Delicious, Granny Smith, Dorset, Yataka, and Chinago (Anna) are the most widely grown apple cultivars.

Mixed cropping within different apple varieties and other annual and perennial crops is the adopted practice in the study district. Purposively, farmers use mixed cropping to accommodate the shortage of farm size and soil fertility, but extensions from the Bureau of Agriculture and Kalihiwot Church introduced the use of different varieties in the orchard and mixed cropping as a management option for diseases and insect pests of apples. Among the total orchards assessed, only 28.05% were monocropped (only apple varieties were planted), while the remaining 71.95% were mixed with different annual and perennial crops. Crops mixed with apples in mixed cropping systems were enset, legumes (fava beans, field peas, and common beans), horticultural crops (cabbage, Brassica species, onion, shallot, garlic, spices, potatoes, herbs, and carrots), and cereals (triticale, barley, and wheat). Totally, 12.20%, 42.68%, 9.76%, and 7.32% were apple mixed with enset, horticulture, cereals, and legumes, respectively. Most orchards were mixed with more than one crop belonging to a family or different families.

Farmers use animal manure, crop residue, and other decomposition of dead materials as organic nutrients to manage apple fruits. In inspected orchards, an average of 4 kg/apple tree of organic fertilizers were applied twice or once a year, and none of the farmers use inorganic fertilizers for apple production. Among the assessed orchards, 48.78% were earthen-up and applied compost once a year, and the remaining 51.22% were earthen-up and applied compost twice a year. All inspected orchards receive organic fertilizer and earthen-up at least once a year. The age of trees in the surveyed areas varied from 3 to 30 years. Among the assessed fields, 72 (43.90%) orchards had trees of various ages in each orchard, while the remaining 92 (56.1%) orchards were uniform in age. Moreover, only 2.44% of observed orchards were below 5 years, and the remaining orchards, 10.97%, 29.27%, and 57.32%, were 5–10, 11–15, and > 15 years, respectively.

Weed management varied from orchards, in which 10.97%, 20.73%, and 68.29% of orchards were poor (high weed infestation), intermediate (orchards with few weeds), and good (weed-free orchards), respectively. A hundred percent of farmers use manual hand weeding for weed management in study areas. *Guizotia scabra*, *Amaranthus* spp., *Cyperus rotundus*, *Cyperus sculantus, Cynodon dactyl, Digitaria ternate,* and *Galinsoga* spp. were the dominant and frequently observed weeds. Disease management practices observed in assessed orchards were pruning + field sanitation and sanitation only (without pruning). Field sanitation includes burying infected plant parts, smoking infected fruits (orchards), removing plant residue and diseased plants from orchards, and pruning practice includes the removal of all diseased parts, overcrowded branches, and non-productive dried twigs from apple trees, plus sanitation, which were major practices applied to control disease in the study area. Among the inspected orchards, 26.83% and 31.71% were for field sanitation and pruning fruit trees for disease management purposes, respectively. However, 41.46% of inspected growers did not apply sanitation practices or prune trees for the management of apple diseases.

Out of the inspected orchards, 23.17%, 45.12%, and 31.71% were noted as high, medium, and low disease infestations, respectively. Apple fruits at the time of the survey showed flowering, fruit development, and fruit maturity growth stages. Farmers obtained apple seedlings from a non-governmental organization (Tolola Kalihiwot Church) (90.24%), and the remaining (9.76%) were sourced from the district Bureau of Agriculture. Most of the aged and susceptible fruits sourced from the non-governmental organization were grafted by MM04 rootstocks. An apple tree planted after 15 years was grafted with relatively resistant MM106 rootstocks, which are currently being multiplied by both the non-governmental organization and the Bureau of Agriculture. Overall field observation indicated that powdery mildew and anthracnose diseases were important factors besides environmental factors that limit apple yields and are responsible for high yield reductions (Table 1).

Apple powdery mildew and anthracnose severity

Powdery mildew and anthracnose diseases were widely distributed, and the diseases were 100% prevalent in all apple fields, irrespective of production years, cultivars

Table 1 Intensity (mean ± SE) and relative importance of powdery mildew and anthracnose of apple for different independent variables in Chencha district of Gamo zone, southern Ethiopia, during the 2021 and 2022 production years

Variable	Variable class	Powdery mildew severity (%)	Anthracnose severity (%)
Altitude[a]	< 2700	20.85 ± 1.29	18.94 ± 1.83
	≥ 2700	28.58 ± 1.48	26.58 ± 1.81
Year	2021	23.56 ± 1.54	22.39 ± 1.96
	2022	28.89 ± 1.62	26.11 ± 1.99
Survey site	Farmers field	26.31 ± 1.16	24.86 ± 1.40
	State farm	22.94 ± 2.87	0.00 ± 0.00
Age of tree	≤ 5 years	19.17 ± 2.84	10.05 ± 5.97
	5 – 10 years	24.59 ± 3.52	18.89 ± 2.86
	10 – 15 years	22.69 ± 1.83	21.33 ± 2.65
	> 15 years	28.64 ± 1.57	27.38 ± 1.88
Source of planting material	Non-government	26.95 ± 1.21	24.49 ± 1.51
	Bureau of Agriculture	19.51 ± 2.54	22.06 ± 3.38
Growth stage	Fruit development	21.81 ± 1.44	20.39 ± 1.64
	Fruit maturity	30.28 ± 1.74	26.22 ± 2.36
	Flowering	34.90 ± 4.17	42.95 ± 4.36
Cropping system[b]	Mono cropped	35.16 ± 2.24	35.96 ± 2.94
	Mixed with Enset	31.15 ± 2.28	32.10 ± 4.55
	Mixed with Horticulture	20.26 ± 1.54	17.95 ± 1.40
	Mixed with Cereals	27.68 ± 2.57	17.10 ± 3.19
	Mixed with Legume	16.62 ± 2.93	12.59 ± 3.88
Apple tree management	Earthen up + compost 1 × /year	36.71 ± 1.24	30.46 ± 2.11
	Earthen up + compost 2 × /year	16.24 ± 1.04	18.34 ± 1.62
Precipitation (mm)	≥ 1000	23.66 ± 1.15	21.38 ± 1.31
	< 1000	40.49 ± 2.22	40.19 ± 4.49
Relative humidity (%)[c]	< 90	24.34 ± 1.14	21.05 ± 1.29
	≥ 90	37.21 ± 3.13	42.93 ± 4.23
Temperature (°C)[d]	< 22	22.77 ± 1.11	19.91 ± 1.24
	≥ 22	38.51 ± 2.41	39.68 ± 3.62
Disease status[e]	High	35.78 ± 2.32	47.38 ± 1.71
	Medium	23.43 ± 1.38	24.64 ± 1.08
	Low	23.22 ± 2.12	6.80 ± 1.48
Disease management	Pruning + sanitation	12.51 ± 1.31	17.44 ± 1.78
	Sanitation (no pruning)	25.91 ± 1.39	25.08 ± 2.94
	No management	36.92 ± 1.37	28.92 ± 2.28
Weed management[f]	Good	24.75 ± 1.37	21.13 ± 1.67
	Intermediate	28.50 ± 2.30	28.61 ± 2.69
	Poor	31.10 ± 3.73	35.47 ± 4.31
Yield (t/ha)	≤ 15	46.87 ± 1.75	52.22 ± 1.76
	15 – 20	33.68 ± 1.33	33.99 ± 1.97
	20 – 25	25.75 ± 2.09	15.09 ± 2.38
	> 25	14.21 ± 1.07	13.28 ± 1.25

[a] Areas of 2300–2700 and ≥ 2700 m.a.s.l are classified as high land and extremely highland, respectively, in Ethiopia

[b] Mono-cropping indicates planting apple varieties only; mixed with enset is apple varieties planted with enset; mixed with horticulture is apple varieties planted with potato, cabbage, spices, aromatic herbs, onion, shallot, garlic, and carrot; mix cropped with cereals is apple varieties planted with wheat, barley, and triticale; and mix cropped with legume is apple varieties planted with fava bean, field pea, and common bean

[c] Relative humidity (%) < 90 and ≥ 90 is the percentage of relative humidity below and above optimum respectively

[d] Temrature (℃) < 22 and ≥ 22 indicates less than and greater than the optimum temperature of both diseases (Xu and Butt 1998; Xu 2021) respectively

[e] High, medium, and low disease status indicate high, medium, and low disease infection in whole observation of orchard respectively

[f] Weed management was recorded as good, intermediate, and poor, referring to weed free, few weeds, and no weeding respectively

grown, and other biophysical factors. However, different levels of severity were observed for different cropping systems, ages of trees, growth stage, weed management practices, altitude, year, disease status and management, source of planting materials, weather variables (precipitation, relative humidity, and temperature), cropping year, tree management practices, and fruit yield over the years. Mean powdery mildew and anthracnose severity were lower in 2021 (23.56% and 22.39%) than in 2022 (28.89% and 26.11%) in that order (Table 1). The maximum (28.64%) mean severity of powdery mildew was recorded at tree ages > 15 years, followed by 24.59% in the age range of 5–10 years. The mean powdery mildew severity of 20.85% and 28.53% was recorded at altitudes of < 2700 and ≥ 2700 m.a.s.l., respectively. Conversely, the mean powdery mildew severity of 35.16%, 31.15%, 20.26%, 27.68%, and 16.62% were obtained from mono-cropped, mixed-cropped with enset, horticulture, cereals, and legumes, respectively.

Mean severity of 21.81%, 30.28%, and 34.90% were noted at fruit development, fruit maturity, and flowering stages, respectively. Similarly, disease management practices and tree management reduced powdery mildew severity. In this regard, pruning practice with sanitation and field sanitation without pruning for disease management reduced powdery mildew severity by 66.12% and 29.82%, respectively, when compared with unmanaged orchards. Earthen-up and composting apples twice a year reduced 55.76% powdery mildew severity as compared with earthen-up and composting once a year. High precipitation ≥ 1000 mm, low relative humidity < 90%, and temperatures < 22 °C reduced powdery mildew severity by 41.56%, 34.58%, and 40.87%, respectively, in two cropping seasons. Generally, powdery mildew severity increased by 22.62% in the 2022 cropping year when compared with 2021 and by 14.69% in farmer orchards as compared to state farm orchards.

On the other hand, the maximum mean severity of anthracnose (27.38%) was observed in orchards covered by trees aged > 15 years, followed by 21.33% in the age range of 11–15 years. The mean anthracnose severity of 35.96%, 32.10%, 17.95%, 17.10%, and 12.59% were recorded in mono-cropped, mixed-cropped with enset, horticulture, cereals, and legumes, respectively. Weed management and disease management practices showed different levels of anthracnose severity. Similarly, mean anthracnose severity of 35.47%, 28.61%, and 21.13% were observed in poor, intermediate, and well-weeded orchards, respectively. The mean severity of 17.44%, 25.08%, and 28.92% were recorded from pruned plus sanitation, well sanitation, and orchards with no disease management applied in that order. The mean severity of anthracnose was 20.39%, 26.22%, and 42.95% were detected from fruit development, fruit maturity, and flowering stages, respectively. For instance, weather variables such as precipitation ≥ 1000 mm, relative humidity < 90%, and temperature < 22 °C reduced the anthracnose severity by 46.80%, 50.96%, and 49.82%, respectively, compared with their counterparts.

The results revealed that in all assessed orchards located at altitudes < 2700 (20.85%), tree age ≤ 5 years (19.17%), sourced from the Bureau of Agriculture (19.51%), in good weed management (24.75%), which intercropped with legume (16.62%), in state farms (22.94%), trees in the fruit development stage (21.81%), earthening up and composting twice in a year (16.24%), and pruning and sanitation (12.51%), precipitation ≥ 1000 mm (23.66%), relative humidity < 90% (24.34%), and temperature < 22 °C (22.77%), 2021 cropping year (23.56%) were obtained relatively the lowest powdery mildew severity as compared with the other variable classes. Similarly, fruit age ≤ 5 years (10.05%), planting materials sourced from the Bureau of Agriculture (22.06%), good weeding (21.13%), intercropping with legumes (12.59%), state farm (0.00%), fruit development stage (20.39%), precipitation ≥ 1000 mm (21.38%), relative humidity < 90% (21.05%), temperature < 22 °C (19.91%), 2021 cropping year (22.39%), and pruning trees and orchard sanitation for disease management (17.44%) significantly reduced the severity of apple anthracnose. This study implies that biophysical factors, for example, young trees under the age of 10 years, good weed management practices, mixed cropping with legumes, seedlings obtained from the Bureau of Agriculture, fruit development stage, earthening and composting twice a year, and pruning unwanted branches and diseased plant parts, reduced both powdery mildew and anthracnose severity in the study area. In both cropping seasons, the apple yield was estimated, and the results varied among the farmers' association, irrespective of biophysical factors. During the study, it was observed that powdery mildew and anthracnose diseases were significantly associated and caused severe yield reductions (Table 1 and Fig. 1). Across farmers' association over production years, results showed that 69.68% and 74.57% yield losses were estimated due to powdery mildew and anthracnose diseases, respectively, compared with the low severity of the two diseases scored.

Association of powdery mildew and anthracnose severity with biophysical factors

The association of independent variables with the mean severity of powdery mildew and anthracnose is summarized in Table 2. Biophysical factors such as the age of the apple tree, cropping system, disease status, disease management practices, weed management, and yield were

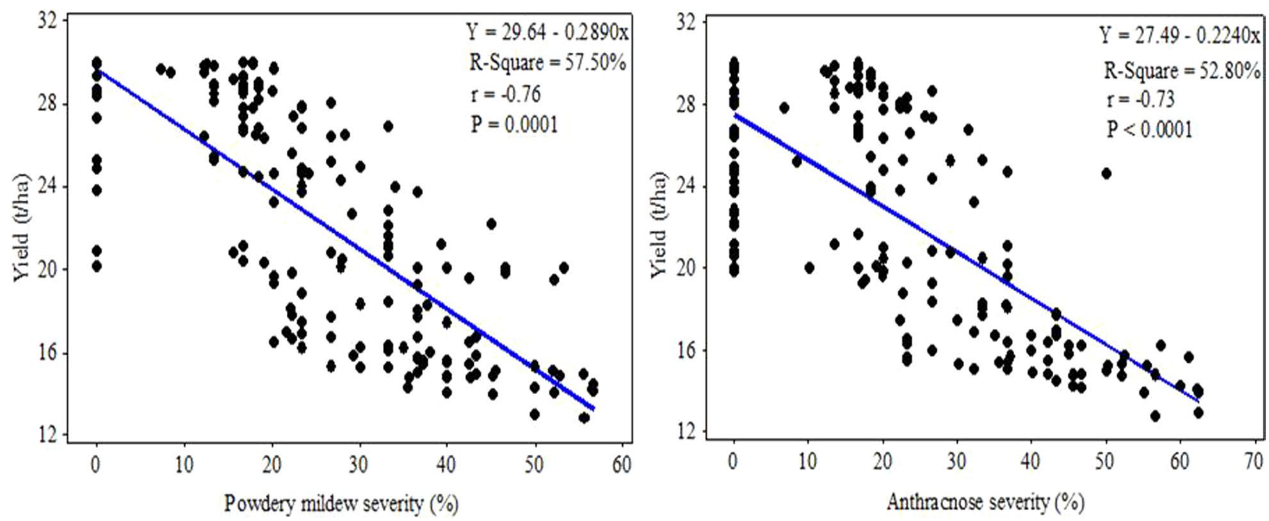

Fig. 1 Linear regression relating powdery mildew and anthracnose severity with apple yield during the 2021 and 2022 production years in Chencha highlands, southern Ethiopia

Table 2 Analysis of the logistic regression model for apples for powdery mildew and anthracnose severity and likelihood ratio tests on independent variables in Chencha district of the Gamo zone, southern Ethiopia, during the 2021 and 2022 production years

Independent variable	df	Severity of apple powdery mildew, LRT				Severity of anthracnose, LRT			
		Type 1 analysis (VEF)		Type 3 analysis (VEL)		Type 1 analysis (VEF)		Type 3 analysis (VEL)	
		DR	$Pr>\chi^2$	DR	$Pr>\chi^2$	DR	$Pr>\chi^2$	DR	$Pr>\chi^2$
Altitude	1	0.37	0.5440	17.14	< 0.0001	6.08	0.0137	11.57	0.0007
Years	1	62.05	< 0.0001	0.89	0.3462	35.80	< 0.0001	6.60	0.0102
Survey site	1	0.01	0.9171	0.35	0.5552	45.91	< 0.0001	45.33	< 0.0001
Age of apple tree	3	62.18	< 0.0001	23.05	< 0.0001	111.90	< 0.0001	9.61	0.0059
Source of planting materials	1	5.36	0.0206	0.78	0.3756	0.05	0.8172	1.02	0.3136
Cropping system	4	148.07	< .0001	50.34	< 0.0001	19.68	0.0006	8.06	0.0346
Growth stage	2	62.76	< .0001	2.87	0.2380	6.61	0.0367	0.74	0.6915
Apple tree management	1	1.93	0.1648	9.42	0.0021	0.99	0.3190	1.42	0.2340
Precipitation	1	46.71	< 0.0001	11.82	0.0006	32.11	< 0.0001	3.07	0.0799
Relative humidity	1	0.00	0.9845	2.11	0.1459	15.26	< 0.0001	6.92	0.0085
Temperature	1	6.45	0.0111	0.06	0.8023	0.09	0.7594	0.12	0.7279
Disease status	2	261.30	< 0.0001	77.45	< 0.0001	2261.79	< 0.0001	743.74	< 0.0001
Disease management	2	266.88	< 0.0001	7.25	0.0266	14.78	0.0006	6.40	0.0496
Weed management	2	36.42	< 0.0001	21.51	< 0.0001	32.81	< 0.0001	33.46	< 0.0001
Yield (t/ha)	3	386.32	< 0.0001	386.32	< 0.0001	83.50	< 0.0001	83.50	< 0.0001

LRT Likelihood ratio test, *VEF* Variable entered first in the model, *VEL* Variable entered last in the model, *DR* Deviance reduction, *Pr* Probability of an x^2 value exceeding the deviance reduction, x^2 = Chi square, *df* Degrees of freedom

very highly and significantly ($P<0.0001–0.05$) associated with the powdery mildew and anthracnose severity when entered first and last into the logistics model. When altitude, year, survey site, and relative humidity were entered first and last into the logistic regression model, they showed a significant relationship with anthracnose severity, while precipitation displayed a very highly significant ($P<0.0001$) association with powdery mildew severity when entered first and last into the model. Also, the source of planting materials, cropping year, growth stage, and temperature showed a significant association with powdery mildew severity when entered into the logistic model as a single variable but lost their significance when entered last into the logistic models. Even though tree growth stage and precipitation presented highly significant relationships with anthracnose severity when entered first into the logistics regression model, they lost their significance when entered last into the model. However, variables such as altitude and tree management practices were highly significantly ($P < 0.001$) associated with powdery mildew severity when entered last into the model, but they lost their significance when entered first into the model. On the other hand, the survey site and relative humidity exhibited a non-significant association with powdery mildew severity when entered first and last into the model. In the same manner, the source of planting materials, apple tree management practices, and temperature showed a non-significant ($P > 0.05$) relationship with anthracnose severity when entered first and last into the logistic model.

Among the independent variables, the age of apple tree ($\chi^2 = 62.18$ and 23.05, 3df), cropping system ($\chi^2 = 148.07$ and 50.34, 4df), precipitation ($\chi^2 = 46.71$ and 11.82, 1df), disease status ($\chi^2 = 261.30$ and 77.45, 2df), disease management practices ($\chi^2 = 266.88$ and 7.25, 2df), weed management ($\chi^2 = 36.42$ and 21.51, 2df), and yield ($\chi^2 = 386.32$ and 386.32, 3df) were the most important variables in their association with powdery mildew severity when entered first and last into the model (Table 2). Although, altitude ($\chi^2 = 6.08$ and 11.57, 1df), yield ($\chi^2 = 83.50$ and 83.50, 3df), tree age ($\chi^2 = 111.90$ and 9.61, 3df), cropping system ($\chi^2 = 19.68$ and 8.06, 4df), year ($\chi^2 = 35.80$ and 6.60, 1df), relative humidity ($\chi^2 = 15.26$ and 6.92 1df), disease status ($\chi^2 = 2261.79$ and 743.74, 2df), disease management ($\chi^2 = 14.78$ and 6.40, 2df), and weed management ($\chi^2 = 32.81$ and 33.46, 2df) were the most important variables in their association with anthracnose severity when entered first and last into the model (Table 2).

The most important variables for both diseases were tested in reduced multiple-variable models. The results of the analysis of deviation for variables and variable classes, standard error, parameter estimate, and odds ratio in a reduced multiple variable regression model test were presented for powdery mildew severity (Table 3) and anthracnose severity (Table 4). In the reduced variable model, the analysis of deviance reduction showed different levels of significance ($P < 0.0001$–0.05) of the association with both powdery mildew and anthracnose severity. Among the tested variables, cropping year, source of planting materials, tree growth stage, temperature, relative humidity, altitude, tree management practices, and survey site lost their significance for the powdery mildew severity association when entered into the reduced multiple regression model (Table 3). In the same trend, tree growth stage, precipitation, source of planting materials, tree management, and temperature lost their significance for anthracnose severity association when entered into a reduced multiple regression model (Table 4).

The probability of high powdery mildew severity (> 26%) was strongly associated with tree age > 15 years, precipitation < 1000 mm, yield ≤ 15 tones/hectare (t/ha), mono-cropped orchards, no disease management practices, high disease status, and poor weed management practices in the study area (Table 3). Also, the probability of high anthracnose severity (> 24%) was highly associated with altitude ≥ 2700 m.a.s.l., tree age > 15 years, the 2022 cropping year, yield ≤ 15 t/ha, farmer orchards, mono-cropped orchards, relative humidity ≥ 90%, no disease management practices, high disease status, and poor weed management practices in the surveyed area (Table 4). Instead, the low powdery mildew severity (≤ 26%) had a probability of strong association with low age of apple tree ≤ 5 years, yield of apple > 25 t/ha, orchard mix cropped with legumes, precipitation ≥ 1000 mm, low level of disease status, disease management practices through appropriate pruning plus sanitation, and weed-free orchards in the study area (Table 3). Also, the low anthracnose severity (≤ 24%) had a probability of strong association with low tree age ≤ 5 years, mid-altitude < 2700 m.a.s.l. 2021 cropping year, good weeded orchards, orchards in the state farm, mix cropped with legumes, yield > 25 t/ha, relative humidity < 90%, low disease status, and cultural disease management practices through pruning with appropriate orchard sanitation in the study area (Table 4). As indicated in Fig. 1, the powdery mildew ($r = -0.76$) and anthracnose ($r = -0.73$) severity were inversely related to apple yields. The linear regression analyses showed that for every one-unit increase in powdery mildew and anthracnose severity, there was 0.2890 and 0.2240 unit decrease in apple yields over the years in that order (Fig. 1).

Discussion

Apple powdery mildew and anthracnose are the major biotic constraints on apple production worldwide. For example, powdery mildew is the major constraint of apple production in the United Kingdom (AHDB 2020), USA (Gañán-Betancur et al. 2021), Germany (Urbanietz and Dunemann 2005), China (Tian et al. 2019), Morocco (Moinina et al. 2019), Hungary (Holb 2009), Kenya (Griesbach 2007), and in Ethiopia (Handoro and Gemu 2007; Fetena and Lemma 2014; Sebsibe and Adimasu 2023; Besufkad et al. 2018), and anthracnose is also a bottleneck of apple production in Washington (Garton et al. 2019), South Korea (Kim et al. 2020), Canada (Braun 1997), and Ethiopia (Handoro and Gemu 2007; Besufkad et al. 2018). Accordingly, the current study found that powdery mildew and anthracnose were distributed in

Table 3 Analysis of deviance, natural logarithms of odds ratio, and standard error of apple powdery mildew severity (%) and likelihood ratio test on independent variables in the reduced regression model in Chencha district of Gamo zone, southern Ethiopia, during the 2021 and 2022 production years

Variables	Residual deviance[a]	df	Powdery mildew LRT		Variable class	Estimate Log_e (odds ratio) [c]	SE	Odds ratio
			DR	$Pr > \chi^2$				
Intercept	2120.56	0	43.69	< 0.0001		−1.689	0.2557	0.184704
Precipitation	1166.53	1	11.85	0.0006	≥ 1000	−0.220	0.0640	0.802519
			–	–	< 1000	0*	0	1.0000
Yield (t/ha)	773.77	3	268.18	< 0.0001	≤ 15	1.720	0.1051	5.584528
			294.47	< 0.0001	15 – 20	1.160	0.0676	3.189933
			107.99	< 0.0001	20 – 25	0.668	0.0643	1.950333
			–	–	> 25	0*	0	1.0000
Age of apple tree	2058.38	3	6.82	0.0090	≤ 5 years	0.353	0.1356	1.423331
			3.00	0.0832	5 – 10 years	0.124	0.0718	1.132016
			9.70	0.0018	10 – 15 years	−0.161	0.0517	0.851292
			–	–	> 15 years	0*	0	1.0000
Cropping system	1648.64	4	0.09	0.7642	Mono cropped	0.029	0.0972	1.029425
			14.97	0.0001	Mixed with enset	0.440	0.1140	1.552707
			0.02	0.8935	Mixed with horticulture	0.012	0.0914	1.012072
			5.40	0.0201	Mixed with cereals	−0.171	0.0737	0.842822
			–	–	Mixed with legume	0*	0	1.0000
Disease status	1797.08	2	44.25	< 0.0001	High	0.572	0.0861	1.771807
			1.99	0.1588	Medium	0.103	0.0734	1.108491
			–	–	Low	0*	0	1.0000
Disease management	1215.17	2	7.05	0.0079	Pruning + sanitation	−0.236	0.0890	0.789781
			3.69	0.0547	Sanitation (no pruning)	−0.124	0.0649	0.88338
			–	–	No management	0*	0	1.0000
Weed management	1550.17	2	1.94	0.1641	Good	−098	0.0710	2.75E-43
			3.76	0.0524	Intermediate	0.148	0.0765	1.159513
			–	–	Poor	0*	0	1.0000

[a] Unexplained variations after fitting the model; LRT = Likelihood ratio test; DR = Deviance reduction; Pr = Probability of an x^2 value exceeding the deviance reduction; [c] * Reference group; df = Degrees of freedom; x^2 = Chi square

all geographical locations and prevailed in 89.02% and 78.04% of the total assessed orchards, respectively.

Though the relative importance of both powdery mildew and anthracnose varied among different biophysical factors, the highest disease severity of powdery mildew (28.89%) and anthracnose (26.11%) was recorded in the 2022 cropping season, which is greater than (23.56%) and (22.39%) of powdery mildew and anthracnose severity, respectively, recorded in the 2021 growing season. This might be attributed to different weather parameters between the cropping years (Fig. 1). Current studies show that powdery mildew severity is higher in precipitation < 1000 mm than that of ≥ 1000 mm. Conversely, powdery mildew severity was not affected by temperature or relative humidity in the study area. This might be the optimum temperature range (13.87–29.73 °C) and relative humidity (54.64–96.06%) for the pathogen *P. leucotricha* in two cropping seasons in the study area. This suggests that low precipitation and the noted range of temperature and relative humidity are favorable for powdery mildew epidemic development in the study area.

Several scholars reported that the relative humidity range of 40–100% and dryer weather with a temperature range of 18.88–21.66 °C were favorable for powdery mildew disease development (Xu and Butt 1998; Holb 2009; Holb and Füzi 2016). On the other hand, this study revealed that anthracnose severity was higher in relative humidity ≥ 90% than in relative humidity < 90%. The high degree of anthracnose severity in higher relative humidity could be due to continuous rainfall with cloudy weather in the study area, which aggravated the infection and dissemination of *N. malicorticis* in two cropping seasons. Similarly, Moinina et al. (2019), Latorre et al. (2002), and Beresford and Kim (2011) reported that the pathogen *N. malicorticis* spreads and is severe in high rainfall with an extended relative humidity greater than 90%. Moreover,

Table 4 Analysis of deviance, natural logarithms of odds ratio and standard error of apple anthracnose severity (%), and likelihood ratio test on independent variables in the reduced regression model in Chencha district of Gamo zone, southern Ethiopia, during the 2021 and 2022 production years

Variables	Residual deviance[a]	df	Anthracnose LRT		Variable class	Estimate Log_e (odds ratio)	SE	Odds ratio
			DR	$Pr > \chi^2$				
Intercept	3476.83	0	10,803	< .0001		−21.510	0.2070	4.550E-10
Altitude	1097.06	1	11.62	0.0007	< 2700	0.2016	0.0591	1.2233
			–	–	≥ 2700	0*	0	1.0000
Yield (t/ha)	809.47	3	39.69	< .0001	≤ 15	0.644	0.1024	1.9057
			50.25	< .0001	15 – 20	0.479	0.0676	1.6164
			0.12	0.7343	20 – 25	0.024	0.0720	1.0247
			–	–	> 25	0*	0	1.0000
Age of apple tree	3364.93	3	5.77	0.0163	≤ 5 years	−0.447	0.1864	0.6390
			0.06	0.8012	5 – 10 years	−0.020	0.0795	0.9801
			1.73	0.1887	10 – 15 years	−0.070	0.0536	0.9320
			–	–	> 15 years	0*	0	1.0000
Cropping system	1077.38	4	2.82	0.0929	Mono cropped	0.179	0.1068	1.1964
			3.79	0.0111	Mixed with enset	0.187	0.1399	1.2057
			1.03	0.3108	Mixed with horticulture	0.107	0.1059	1.1132
			0.02	0.8953	Mixed with cereals	0.011	0.0873	1.0115
			–	–	Mixed with legume	0*	0	1.0000
Years	1041.58	1	6.59	0.0102	2021	−0.109	0.0427	0.8961
			–	–	2022	0*	0	1.0000
Survey site	962.86	1	4.13	< .0001	Farmers field	21.16	0.0	154810^6
			–	–	State farm	0*	0	1.0000
Relative humidity	893.06	1	6.96	0.0083	< 90	−0.193	0.0733	0.8242
			–	–	≥ 90	0*	0	1.0000
Disease status	1103.14	2	522.24	< .0001	High	−2.269	0.0993	0.1033
			68.99	< .0001	Medium	−0.5972	0.0719	0.5503
			–	–	Low	0*	0	1.0000
Disease management	941.42	2	3.39	0.0237	Pruning + sanitation	−0.111	0.0942	0.8947
			1.39	0.5108	Sanitation (no pruning)	−0.0467	0.0711	0.9543
			–	–	No management	0*	0	1.0000
Weed management	1008.77	2	4.29	0.0384	Good	0.157	0.0759	1.1702
			3.25	0.0713	Intermediate	−0.1496	0.0829	0.8610
			–	–	Poor	0*	0	1.0000

[a] Unexplained variations after fitting the model; *LRT* Likelihood ratio test, *DR* Deviance reduction, *Pr* Probability of an x^2 value exceeding the deviance reduction; * Reference group; df = Degrees of freedom; x^2 = Chi square

secondary infection of *N. malicorticis* is favored by prolonged relative humidity in combination with a moist and warmer environment (Amiri and Gañán 2019), not cold weather, which retards pathogen development (Xu 2021).

Different degrees of powdery mildew and anthracnose severity were observed among the tree ages in the study area. The orchards with aged trees had relatively high disease severity as compared to orchards with fewer aged trees. This might be due to the higher crop defense mechanisms in younger trees than in older ones. Similar reports have been made by Arrigon et al. (2018) and Arrigon et al. (2020), where young apple trees strongly defend the pathogen community, which adversely affects the epidemics of apple diseases. Even though it is difficult to quantify the varieties' response in the model due to the uneven mixture of numerous varieties among the assessed orchards, visually, varieties such as Red delicious, Chencha gala, Royal gala, Prima, Fuji, Bonded red, and Jonafree were shown to have low powdery mildew infestation (tolerant), Bartlett pear, Golden delicious, Granny smith, Crispin, Yataka, and Princess were relatively moderate (moderate powdery mildew infestation), and all other varieties cultivated in the study area were susceptible to very highly susceptible reactions for powdery mildew disease development. Likewise, Crispin, Chencha gala, Royal gala, and Fuji were shown to have low anthracnose infestations (tolerant). The Prima, Princess, Red delicious, and Yataka were moderately infected by anthracnose, and all the remaining varieties showed different degrees of susceptibility to anthracnose epidemics in the study area. The different response reactions to two diseases might be due to the genetic variability of host (apple) varieties among each other and the variability between the two diseases. This study confirmed the previous findings of Arrigon et al. (2018), who demonstrated that plant pathogens were affected by host genotype and fungal genera.

Apple orchards were mixed with various annual and perennial crops and showed significant variation in both disease epidemics. In mixed-cropped orchards, disease intensity is lower than in mono-cropped orchards. Mix cropped with horticulture and legumes reduced the powdery mildew severity by 42.38% and 52.73% and the anthracnose severity by 50.08% and 64.99%, respectively, compared to mono-cropped orchards. In this study, district apple mix cropping is purposefully applied to manage soil fertility and apple pests and diseases (Temesgen 2017; Beyene et al. 2022). Similarly, an experimental study in India by Bhat et al. (2018) reported that apples intercropped with legumes showed better agronomic performance and yield than the control (mono-cropped). Mixed cropping of apples with others (especially by covering free space with legumes and horticultural crops) was applied to reduce disease epidemics in Ethiopia (Besufkad et al. 2018; Sebsibe and Adimasu 2023). The economic analysis also indicated intercropping with legumes had a better cost–benefit ratio, followed by intercropping with horticultural crops, than mono-cropping (Bhat et al. 2014, 2018; Rifat et al. 2018). After two years of study in China, Zhao et al. (2022) demonstrated that mixed cropping with different Allium and Brassica species improved the growth of apples and alleviated apple repellant diseases.

This study also demonstrated that the highest anthracnose severity was recorded in farmer orchards compared to state orchards. This might be due to the regular monitoring and careful management applied by skilled men on state farms (especially in Kalehiwot Church) rather than farmers' orchards. Kalehiwot churches in the district are well skilled in apple production and protection, since it is the first anniversary of apple production in the country of Ethiopia in the case of the missionary at Tolola church 70 years ago. In church, there are experts in apple production and protection, and their orchards are less infected than farmers' orchards.

This study showed that disease management practices applied to control the epidemics of apple diseases in surveyed areas significantly reduced the severity of powdery mildew and anthracnose as compared to no management applied to orchards. Among the given disease management practices applied, pruning and sanitation reduced 66.12% of powdery mildew severity and 39.69% of anthracnose severity compared to non-managed orchards. The output of the current study is strongly in line with the findings of Holb (2005) and Marine et al. (2010), where the removal of primary inoculum sources through pruning and sanitation reduced the severity of apple powdery mildew. Hence, pruning and sanitation include the removal of fallen infected plant debris, which significantly reduces secondary infection (Holb and Füzi 2016). Similarly, different authors reported that pruning and sanitation were found to reduce anthracnose diseases in orchard conditions (White 1922; O'Rourke 2001; Saville and Olivieri 2019; Downer et al. 2020). In addition, pruning opens the canopy, which reduces the relative humidity under shoots and the branch microclimate, which is an unfavorable condition for foliar disease infections (Cooley et al. 1997).

In this study, weed management significantly influenced the intensity of powdery mildew and anthracnose diseases. Good-weeded orchards reduced 20.41% and 40.43% powdery mildew and anthracnose severity, respectively, compared with poor-weeded orchards. This might be due to the direct and indirect effects of weeds on host plants (apples) and microclimate. Many investigators agree that weeds directly compete with apple trees for resources and indirectly weaken the entire tissue, which makes apples susceptible to various pathogens (Temesgen 2017; Dudic et al. 2020); weeds are the alternative hosts for pathogens and facilitate disease infestation by favoring the conditions for pathogens (Mathews et al. 2002; Verma 2014; Samnegård et al. 2019; Dudic et al. 2020). Overall, in the current study, the analysis of the logistics regression model confirmed that the age of the apple tree, cropping system, weed management, disease management practices, and fruit yield were significantly associated with the severity of powdery mildew and anthracnose. Survey site, cropping year, relative humidity, and altitude were also significantly associated with anthracnose severity, while precipitation was highly significantly associated with powdery mildew epidemics. These variables are found to play an important role in the development of disease epidemics, either alone or in combination. The model also quantified that some of the variables significantly hindered the disease epidemics compared to other variables.

Conclusion

Powdery mildew and anthracnose diseases were widely distributed as important restraints of production in the main apple-growing areas of Chencha highlands, southern Ethiopia, suggesting that the diseases continued to be a major threat to apple production in the areas. Current studies have found that different biophysical factors have a significant influence on both powdery mildew and anthracnose epidemic development. The predictor variables such as the age of the tree, cropping systems, disease status, and disease and weed management together had significant associations with high powdery mildew (> 26%) and anthracnose (> 24%) severity and were identified as among the most important factors for infection and epidemic disease development. Thus, the results could serve as a foundation for developing a sustainable management strategy for powdery mildew and anthracnose to secure apple production in the study area and similar agro-ecologies elsewhere. However, regular disease surveillance should be conducted each year during the production seasons to determine the impact of rhythmic dynamics and changes to growth conditions, fertilizations, varieties, growth stages, cropping systems, and other agronomic practices on disease development and related effects on apple productivity.

Methods

Description of the study area

The assessment of powdery mildew and anthracnose epidemics and influencing factors such as the age of the tree, agronomic practices, disease management practices, cropping system, and other important factors were conducted in the Chencha highlands of the Gamo zone in southern Ethiopia during the 2021 and 2022 production years. Chencha is the first and most potential place for apple production, particularly in the region and in Ethiopia as a whole. Chencha district is mainly characterized by a crop-livestock mixed farming system (Beyene et al. 2022). Farmers in the district are well experienced in the use of animal manure and crop residue as organic fertilizer and crop residue for feed. The altitudes of the district range from 1800 to 3700 m.a.s.l. Total rainfall, relative humidity, and monthly maximum and minimum temperature data for the district were obtained from the Ethiopian Meteorological Agency, Hawassa Branch, and summarized as follows (Fig. 2).

Survey methodology and sampling units

Necessary information for powdery mildew, anthracnose, and biophysical factors of the orchards was collected by directly inspecting apple orchards and interviewing growers. With some adjustments to the process, a multistage random sampling strategy was followed to gather the data that were required in the study. Only the administrative zone, the districts, and the farmer associations

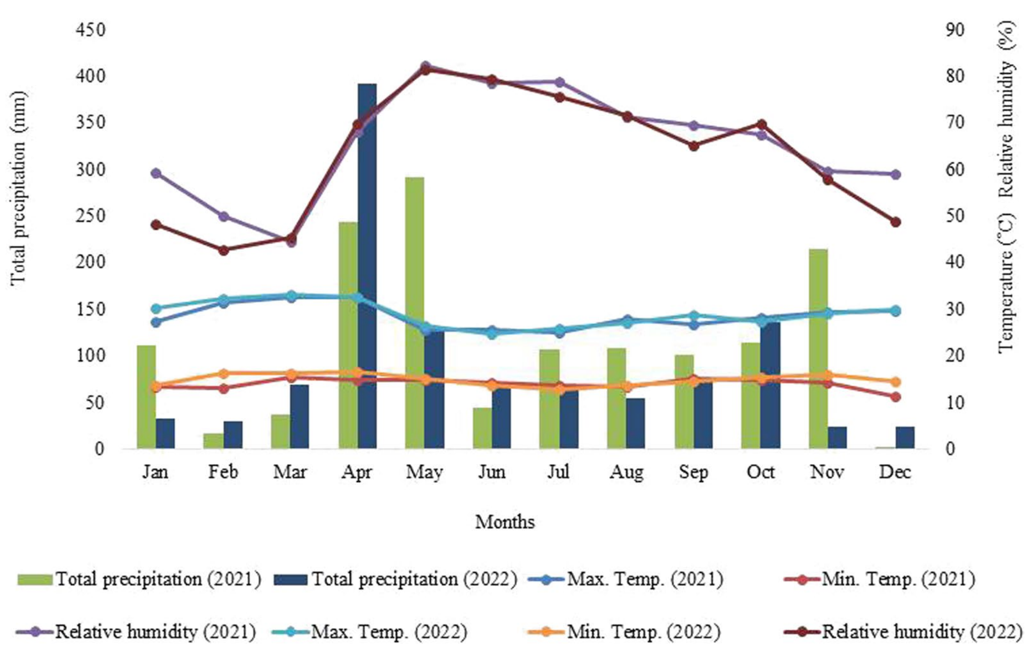

Fig. 2 Total precipitation (mm), relative humidity (%), and maximum and minimum temperature (°C) in the Chencha district, southern Ethiopia, during the 2021 and 2022 production years

that were severely affected by the target diseases in the area were included in the survey study. Accordingly, among the thirty-three potential apple-producing farmer associations in the district, the top five farmer associations (the lowest administrative level in Ethiopia), namely (Chencha-02, Kale, Losha, Yora, and Mesho), were purposefully selected for this study.

Based on the area coverage, the assessment was conducted on 36, 34, 32, 32, and 30 orchards in Chencha 02, Kale, Losha, Yora, and Mesho farmers' associations, respectively. In total, 164 apple orchards were inspected from flowering to the fruit development stage in two consecutive years. In this study, apple orchards were purposefully selected at 2–3 km along accessible rural roads. In purposefully selected orchards, ten apple trees were sampled by moving in W fashions and taken as sample units. All selected apple trees were inspected for the presence or absence of external signs and symptoms. The intensity of the two diseases was recorded from 10 randomly selected apple trees. In addition to disease parameters, other biophysical information was collected using a pre-developed questionnaire. The growers were visited, and all plant parts (roots, stems, leaves, and fruits) were assessed for the presence of any external signs of powdery mildew and symptoms of anthracnose.

All necessary information, such as GPS point, age of the tree, tree management, weed management, cropping system, source of planting materials, growth stage, disease management practices, and estimated yield (t/ha), was recorded using the data collection questionnaire. Based on overall observations, the orchards were estimated to have high, medium, and low disease infestations. Similarly, weed free, orchards with few weeds, and orchards with high weed infestations were noted as good, intermediate, and poor weed-managed orchards, respectively. All the apple stands in each orchard were considered sampling units for powdery mildew and anthracnose intensity and biophysical factor valuation. Disease samples of infected apple leaves and stem bark with typical signs and symptoms were taken from each orchard. The collected samples were packed individually in sterile paper bags, labeled, and brought to the Arba Minch Crop Protection Clinic to identify and confirm the causal pathogen. Using potato dextrose agar medium and established methods for fungus isolation, pathogen identification was carried out.

Diseases assessment

The assessment was carried out at the time of the active growth stage, flowering, fruit development, or maturity stages of the apple. The disease severity is visually estimated by the percentage of damaged plant parts throughout the whole plant. The severity of apple powdery mildew was recorded using the 0–6 visual rating scale suggested by Spencer (1977), where 0 = no infection, 1 = ≤ 1% infection, 2 = 2–5% infection, 3 = 6–20% infection, 4 = 21–40% infection, 5 = > 40% infection, and 6 = 100% infection. Similarly, the severity of anthracnose is rated on a 0–5 rating scale, where 0 = no infection, 1 = 1–20% infection, 2 = 21–40% infection, 3 = 41–60% infection, 4 = 61–80% infection, and 5 = more than 81% infected (Garton et al. 2019). The recorded data is converted to percentages by the formula as follows:

$$\text{Disease severity } (\%) = \frac{\text{Sum of numerical ratings}}{\text{Number of plants scored} \times \text{maximum score on the scale}} \times 100.$$

Data analysis

A descriptive statistic was used to describe the distribution, relative importance, and association of powdery mildew and anthracnose intensity with biophysical factors. The severity of both diseases was classified into distinct groups of binomial qualitative data, as suggested by Yuen (2006). Contingency tables for disease severity and independent variables are represented by the bivariate distributions of the fields (Table 5). The grand mean values of 26% and 24% for powdery mildew and anthracnose severities are used as boundaries for binary classification. The class boundaries of (≤ 26% and > 26%) and (≤ 24% and > 24%) were taken for powdery mildew and anthracnose severity, respectively. The association of disease parameters with biophysical factors was analyzed using SAS statistical software version 9.3 (SAS, 2014) using a logistic regression model (Yuen 2006). The effects of independent variables on disease severity were evaluated in a single-variable model and reduced in multiple-variable models (Yuen 2006).

The influence of independent variables on the severity of diseases was evaluated three times. First, a single-variable model was used to determine the relationship between an independent variable and the severity of anthracnose and powdery mildew. After that, the relationship between each independent variable and the severity of anthracnose and powdery mildew was examined by placing them in the multiple models first and last, respectively, relative to all other independent variables. In order to illustrate the significance of particular variable classes, independent variables that had a strong correlation with the severity of anthracnose and powdery mildew were progressively included in a reduced multiple-variable model (Yuen 2006). The parameter estimates and standard errors of the parameter estimates were analyzed using the GENMOD procedure for single and multiple models. Deviance reduction and odds ratios were figured for independent variables as they were added to the reduced multiple-variable models. By exponentiating the parameter estimates for comparing the effect based on a reference point, the odds ratio was

Table 5 Categorization of independent variables and disease contingency for powdery mildew and anthracnose severity in Chencha, southern Ethiopia, during the 2021 and 2022 cropping years

Variable	Variable class	Number of fields	Powdery mildew severity (%)		Anthracnose severity (%)	
			≤ 26	> 26	≤ 24	> 24
Altitude[a]	< 2700	50	35	15	38	12
	≥ 2700	114	50	64	56	58
Year	2021	82	49	33	52	30
	2022	82	36	46	42	40
Survey site	Farmers field	160	83	77	90	70
	State farm	4	2	2	4	0
Age of tree	≤ 5 years	4	3	1	4	0
	5 – 10 years	18	8	10	12	6
	10 – 15 years	48	30	18	32	16
	> 15 years	94	44	50	46	48
Source of planting material	Non-government	148	74	74	84	64
	Bureau of Agriculture	16	11	5	10	7
Growth stage	Fruit development	84	53	31	53	31
	Fruit maturity	70	28	42	40	30
	Flowering	10	4	6	1	9
Cropping system[b]	Mono-cropped	46	11	35	12	34
	Mixed with enset	20	6	14	8	12
	Mixed with horticulture	70	50	20	42	28
	Mixed with cereals	16	8	8	12	4
	Mixed with legume	12	10	2	10	2
Apple tree management	Earthen up + compost 1 × /year	80	14	66	36	44
	Earthen up + compost 2 × /year	84	71	13	58	26
Precipitation (mm)	< 1000	139	82	57	90	49
	≥ 1000	25	2	23	5	20
Relative humidity (%)[c]	< 90	140	80	60	89	51
	≥ 90	24	6	18	5	19
Temperature (℃)[d]	< 22	128	80	48	87	41
	≥ 22	36	6	30	7	29
Disease status[e]	High	38	10	28	1	37
	Medium	74	45	29	44	30
	Low	52	31	21	49	3
Disease management	Pruning + sanitation	52	49	3	38	14
	Sanitation (no pruning)	44	23	21	24	20
	No management	68	13	58	31	37
Weed management[f]	Good	112	64	48	73	39
	Intermediate	34	16	18	18	16
	Poor	18	5	13	4	14
Yield (t/ha)	≤ 15	19	0	19	0	19
	15 – 20	48	12	36	12	36
	20 – 25	36	17	19	27	9
	> 25	61	56	5	56	5

[a] Areas of 2300–2700 and ≥ 2700 m.a.s.l are classified as highland and extremely highland, respectively, in Ethiopia

[b] Mono-cropping indicates planting apple varieties only; mixed with enset is apple varieties planted with enset; mixed with horticulture is apple varieties planted with potato, cabbage, spices, aromatic herbs, onion, shallot, garlic, and carrot; mix cropped with cereals is planted with wheat, barley, and triticale; and mix cropped with legume is apple varieties planted with fava bean, field pea, and common bean

[c] Relative humidity (%) < 90 and ≥ 90 is the percentage of relative humidity below and above optimum, respectively

[d] Temrature (℃) < 22 and ≥ 22 indicates less than and greater than the optimum temperature of both diseases (Xu and Butt 1998; Xu 2021), respectively

[e] High, medium, and low disease status indicate high, medium, and low disease infection in the whole observation of orchard, respectively

[f] Weed management was recorded as good, intermediate, and poor, referring to weed free, few weeds, and no weeding, respectively

calculated (Yuen 2006; Mengesha et al. 2018). The single- and multiple-variable models were compared using the deviation, which is the logarithm of the ratio of two likelihoods. The significance of the variable was assessed by comparing the results of likelihood ratio tests (LRTs) to the Chi-square value (McCullagh and Nelder 1989). Independently, linear regression was employed to determine the relationship between powdery mildew and anthracnose severity and apple yields. It estimates how apple yields change as the magnitude of powdery mildew and anthracnose changes. Linear regression analyses were appraised using MINITAB® software version 14 (Release 14.20 for Windows® 2007).

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Author contributions
AA and GG: Conceptualization, methodology, writing the original draft manuscript and editing. AA, GG, ZF, and BB: Conducting field investigation, validation, data curation and analysis. All authors have read and agreed to the published final version of the manuscript.

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Availability of data and materials
All data generated from this study is included in the manuscript. Further data sets are available from the corresponding author upon reasonable request.

Declarations

Ethical approval and consent to participate
Not applicable.

Consents for publication
Not applicable.

Competing interests
The authors declare that the research was conducted in the absence of any commercial or financial considerations that could be construed as a potential conflict of interest.

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