A new systemic approach for promoting soil and plant health in *Actinidia chinensis* var. *chinensis* orchards to face kiwifruit vine decline syndrome (KVDS)

A. Sofo[1,a], B. Dichio[1], A.N. Mininni[1], I. Tomasi[2], C. Scotti[3], S. Green[4], A.C. Tuzio[1], D. Laterza[1], R. Di Biase[1], M. Calabritto[1], C. De Virgilio[5], C. Manzari[5], E. Xylogiannis[6], I. Donati[7] and M. Mastroleo[7]

[1]Department of European and Mediterranean Cultures (DiCEM), Università degli Studi della Basilicata, via Lanera 20, 75100 Matera, Italy; [2]Vitaceres SAS Consultante, Lotissement les Mourgues 17, 30920 Codognan, France; [3]I.TER Soc. Coop. a.r.l., Via Zacconi 12, 40127 Bologna, Italy; [4]Plant and Food Research, Mount Albert, Sandringham 1025, New Zealand; [5]Department of Biosciences, Biotechnology and Environment (DBBA), Via Orabona 134, 70125 Bari, Italy; [6]Independent researcher, 47522 Cesena (FC), Italy; [7]Zespri Innovation Ltd, 400 Manganui Road, PO BOX 4043, Mt. Manganui South 3116, New Zealand.

Abstract

Italy, the third largest producer of kiwifruit in the world, lost 30% of its production in recent years because of the spread of the kiwifruit vine decline syndrome (KVDS). Although the etiology of KVDS is still not clear, it is often associated with water excess and stagnation. We hypothesize that soil compaction or soil structure disruption associated with hypoxia and hyper oxidation could have a priming effect in the emergence of KVDS. To investigate the causal factors and potential solutions to counter KVDS, a multi-disciplinary experimental trial was undertaken in a kiwifruit orchard (*Actinidia chinensis* var. *chinensis* 'Zesy002') affected by KVDS in Latina (central Italy). After a first phase of fundamental agronomic practices, such as water drainage and precision irrigation (relevant to remove excess water and reduce the water table), nature-based solutions were applied: decompacting crops for increasing water permeability, organic amendments' application. Also, following a deep study on the root physiology, a root pruning approach was been tested for improving root regeneration. The adoption of sustainable agronomic practices ameliorated the general physiological status of the plants (+46.1% of healthy plants measured at the end of the three-year trial). The results of this project demonstrated that a sustainable and agroecological approach to kiwifruit orchard management can represent a technically feasible solution to halt the spread of KVDS by recreating the natural environmental conditions where kiwifruit plants thrive. A holistic approach was applied to face KVDS, considering plants as an integrated system with soil and atmosphere.

Keywords: compost addition, green manure, precision irrigation, root microscopy, root pruning, soil macroporosity, soil redox potential, water excess

INTRODUCTION

The Italian kiwifruit industry, a prominent player in the fruit growing sector since 1970, faces a serious threat known as "kiwifruit vine decline syndrome" (KVDS), causing a 30% decrease in Italian kiwifruit production. KVDS, linked to factors like waterlogging, soil compaction, root hypoxia, and phytopathogens, also raises concerns in other countries (Savian et al., 2020; Sofo et al., 2022).

Climate change, particularly high temperatures and unbalanced distribution of rainfall during the year, with a concentration in the fall-winter months, are suggested as contributing factors to KVDS (Bardi, 2020; Bardi et al., 2020). Symptoms resembling KVDS were observed in New Zealand in 1989, attributed to poor soil oxygenation and kiwifruit root sensitivity (Smith et al., 1989; Reid et al., 1991). KVDS symptoms include epinasty, chlorosis, desiccation,

[a]E-mail: adriano.sofo@unibas.it

and plant decline because of root system damage (Bardi et al., 2020; Sofo et al., 2022). Mismanagement of soil and water, resulting in compacted, impermeable, and hypoxic soil, appears to be a major cause of KVDS (Bardi, 2020; Savian et al., 2020; Sofo et al., 2022). Soil microorganisms, implicated in bacterial canker and fungal pathogens, might contribute to or result from KVDS conditions (Donati et al., 2014; Savian et al., 2021). However, their role in field conditions remains unclear.

A holistic approach to healthy agroecosystems involves redefining internal and external interactions and identifying soil health indicators, emphasizing the importance of redox potential (Eh) and acid-base reactions (Husson et al., 2021). Maintaining specific Eh-pH conditions in the soil rhizosphere is crucial for root health, and plants immobilize energy to correct these parameters in the rhizosphere (Husson et al., 2018). To address KVDS and understand the role of soil fertility, a set of sustainable agronomic practices, including root pruning, organic matter addition, and cover crops, are proposed. Research objectives included a microscopic assessment of root damage, an evaluation of soil Eh-pH and macroporosity, and an overall plant physiological status evaluation through visual scoring.

MATERIALS AND METHODS

The experimental kiwifruit orchard was in Sermoneta, Italy (41°33’30.72”N; 12°57’18.51”E), an area with an average annual ETo of 732 mm and an annual rainfall of 1,113 mm. *Actinidia chinensis* var. *chinensis* ‘Zesy002’, a yellow-fleshed kiwifruit grafted onto ‘Hayward’ rootstocks (*Actinidia chinensis* var. *deliciosa*) in 2013, was planted. The planting density was 3×5 m in row and inter-row, totaling 660 plants ha^{-1}, irrigated with a double drip system and sprinkler system. The three-year experimental trial began in February 2021. Soil physicochemical parameters measured in February 2021 and in February 2023 are reported in Table 1. At the experiment’s outset, two areas were identified in the orchard: one with severe visual symptoms of the KVDS (KVDS group) and another with healthy plants (CTRL group). Severe KVDS symptoms included phylloptosis, shoot wilting, fruit size reduction, and esthetic defects making the fruits unmarketable.

From the second year (2022) onward, sustainable agronomic practices were applied on KVDS-symptomatic vines to mitigate/avoid KVDS progression. Practices included root pruning, specific cover crops, manure addition, optimization of irrigation and water drainage. An innovative irrigation strategy based on a water-balance method with a feedback adjustment mechanism using continuous soil moisture measurements has been applied (irrigation volume = approx. 4,800 m^3 ha^{-1} $year^{-1}$) (Mininni et al., 2022). Root pruning involved a deep vertical cut of roots 70 cm from the trunk on all four sides of the plant (Figure 1).

Figure 1. Excavation showing kiwifruit roots (left) before root pruning and (right) after root pruning.

Table 1. Soil physicochemical parameters measured at the beginning of the experiment in February 2021 (A) and in February 2023 (B) in the KVDS and CTRL plots. Each value is the average of three replicates (*n*=9).

A (February 2021)	**KVDS**		**CTRL**	
	0-30 cm	**30-60 cm**	**0-30 cm**	**30-60 cm**
pH	7.4	7.3	6.9	6.7
Electrical conductivity (mS cm^{-1})	0.242	0.148	0.505	0.371
Organic matter (%)	3.39	2.60	3.07	2.85
Total limestone	traces	traces	traces	traces
Skeleton	traces	absent	traces	absent
Macroporosity (%)	8.51	4.90	12.35	7.40
Eh_{pH7} (mV)	519	562	537	592
Soil texture				
Sand (2.0-0.020 mm) (%)	25	24	33	29
Silt (0.020-0.002 mm) (%)	32	32	29	32
Clay (<0.002 mm) (%)	43	44	39	40
Soil texture	clay	clay	clay	clay
Nutrients				
N total (%)	0.195	0.153	0.180	0.161
P absorbable (ppm)	41	22	37	31
Fe absorbable (ppm)	15.8	17.2	35.5	40.0
Mn absorbable (ppm)	28.1	27.6	56.1	65.9
Cu absorbable (ppm)	4.2	2.7	3.9	3.7
Zn absorbable (ppm)	3.0	0.8	4.3	4.0
Ca exchangeable (ppm)	4,133	3,900	4,353	4,920
Mg exchangeable (ppm)	600	567	480	493
K exchangeable (ppm)	134	96	203	143
Na exchangeable (ppm)	87	80	100	95
Cation exchange capacity				
CEC (meq 100 g $soil^{-1}$)	26.39	24.82	27.03	30.49
Ca (meq 100 g $soil^{-1}$)	20.67	19.50	21.77	24.61
Mg (meq 100 g $soil^{-1}$)	5.00	4.72	4.00	4.10
K (meq 100 g $soil^{-1}$)	0.34	0.25	0.52	0.36
Na (meq 100 g $soil^{-1}$)	0.38	0.35	0.43	0.42
Base saturation (%)	100	100	98.9	96.5
B (February 2023)	**KVDS**		**CTRL**	
	0-20 cm		**0-20 cm**	
pH (water)	7.4		7.5	
pH_{KCl}	6.6		6.7	
Organic matter (%)	4.1		3.1	
Total limestone	<1		<1	
Nutrients				
N total (%)	2		1.7	
P Olsen (ppm)	64		80	
Mg exchangeable (ppm)	573		527	
Ca exchangeable (ppm)	4934		4345	
K exchangeable (ppm)	423		374	
Na exchangeable (ppm)	70		52	
	CEC calculated	**CEC cobalt-hexamine extraction**	**CEC calculated**	**CEC cobalt-hexamine extraction**
CEC (meq 100 g $soil^{-1}$)	15.6	25.4	12.7	21.4
Ca (%CEC)	62.4	98	63.1	102
Mg (%CEC)	28.8	18.8	29	20.5
K (%CEC)	6.9	4.3	6.1	4.5
Na (%CEC)	1.9	1.2	1.8	1.1
Base saturation (%)	100	100	100	100
Eh_{pH7} (mV)	**KVDS 10 cm**	**KVDS 25 cm**	**CTRL 10 cm**	**CTRL 25 cm**
April 2023	526	539	466	506
May 2023	496	537	491	543
June 2023	533	566	522	558

In KVDS plants, three green manure cycles were conducted between March 2021 and April 2023 at the dose of 4 t ha^{-1} on the row in February; cover crops were sown on the entire surface from December to June. The cover crop mixture is detailed in Table 2. The cover crop was destroyed at the end of June after growing up to 1 m high. Immediately after green manure sowing, mature manure was distributed at a rate of 80 q ha^{-1}. A drainage system, informed by water table monitoring with piezometers since early 2021, was implemented (Figure 2).

Table 2. Composition of the applied cover crops.

Species	Cultivar	Weight (%)
Avena strigosa	Iapar	40
Raphanus sativus	Cassius	30
Eruca vesicaria	Rocket	10
Sinapis alba	Rumba	10
Brassica juncea	Terminator	10

Figure 2. Excavations for the setting-up of the water drainage plant.

In the CTRL group, from 2021 to 2023, there was only spontaneous grasses mowed in April, June and September at 40 cm high and no green manure input. Irrigation in the CTRL group was applied empirically, with average values of 10,000-12,000 m^3 ha^{-1} $year^{-1}$.

In February 2021, fine root samples were collected from healthy plants (CTRL) and KVDS-affected plants (KVDS) for light microscopy analysis. Furthermore, soil samples were taken at 0-30 and 30-60 cm depths for redox potential and macroporosity analysis. Soil redox potential was measured in dried soil samples in the laboratory reading in the supernatant from soaking soil for 5 h in distilled water (ratio 1:2.5) using a potentiometric method, and macroporosity was assessed through transmitted light microscopy (Sotta and Fujiwara, 2017).

In 2023, a first campaign of measurements of the soil redox potential with pH was made in April, May and June, in the two modalities, using a portable potentiometric method made of two voltmeters (WTW3110, WTW, Weilheim, Germany) with an input resistance greater than 5X1012 Ohm, two reference electrodes (radiometer analytical Ag/AgCl KCl 3 M, ref 321) and two simultaneous measuring depths in the ground at 10 and 25 cm with a 45-cm-long handmade probe with two pure platinum redox sensors (Husson et al., 2016). Soil redox potential was measured simultaneously at the two different depths by connecting each Pt sensor to a different voltmeter and reference electrode, and each modality was measured at 10 different points in the rhizosphere area. The values noted according to the Ag/AgCl (EAg/AgCl) reference electrode were transformed to give Eh according to the normal hydrogen electrode (NHE), and secondly the value of Eh was corrected at pH 7. Using Eh_{pH7} allows to compare the redox potential of soils while avoiding the impact of pH on the Eh value.

To assess the progression or regression of plant physiological status throughout the trial, the sustainably managed orchard section (KVDS block) and the control block (CTRL) underwent analysis using a scoring system. Both female and male plants were visually categorized into four groups based on KVDS symptoms on leaves, the number and vitality of new shoots, and overall health status: a) healthy plants (green); b) average plants with moderate canopy vigor and new but feeble shoots (yellow); c) severely compromised plants exhibiting low canopy vigor, absence of new shoots, and KVDS symptoms on leaves (red); d) deceased plants (blue) (refer to Figure 3 for visual representation).

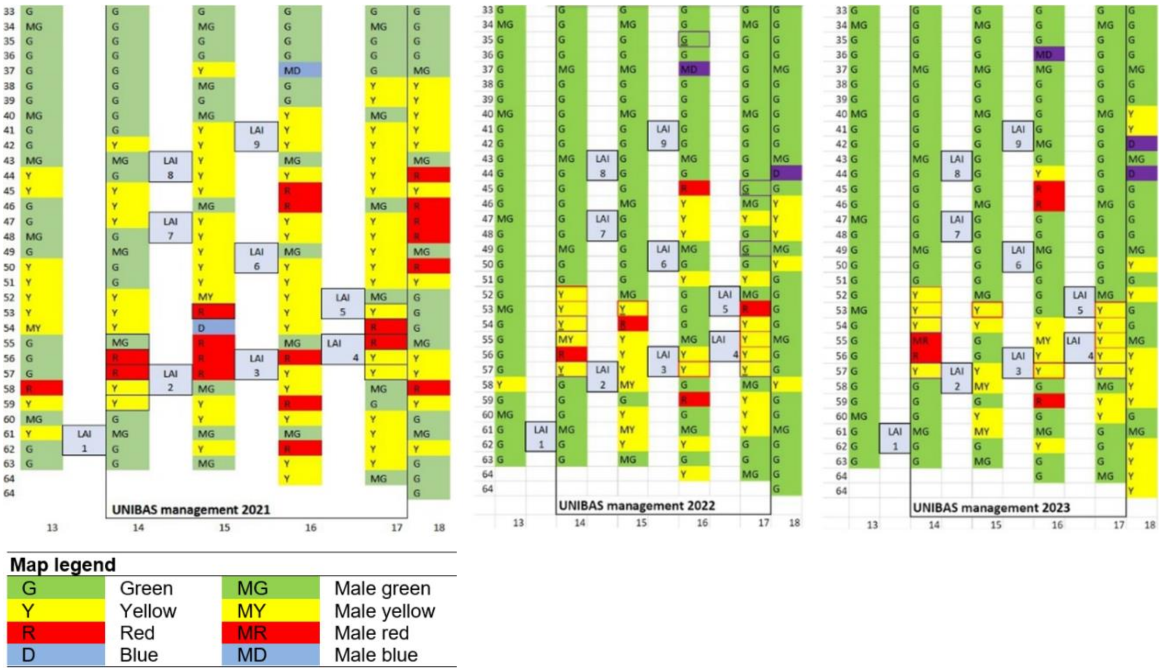

Figure 3. Scoring map of the general physiological status of kiwifruit plants in the KVDS block in 2021, 2022 and 2023. Plant classification: a) healthy plants (green); b) average plants, with medium canopy vigor, new but weak shoots (yellow); c) very compromised plants, with low canopy vigor, no new shoots and KVDS symptoms on leaves (red); d) dead plants (blue).

RESULTS AND DISCUSSION

Given the susceptibility of KVDS soils to compaction and macroporosity loss (Smith et al., 1989; Bardi et al., 2020; Sofo et al., 2022), Eh measurements offer insights into optimal kiwifruit growth conditions. The obtained Eh_{pH7} results (Table 1A) align with values observed in diverse oxidized soils (Husson et al., 2018, 2021). At 0-30 cm, CTRL soils exhibited an EhpH7 of 537 mV, while KVDS soils showed 519 mV. At 30-60, both groups displayed more oxidized soils, with higher Eh_{pH7} values compared to the upper layers. Notably, topsoil Eh_{pH7} in conservation agriculture is often lower than deeper horizons, attributed to high biomass input on the soil surface. Despite lower macropores in deeper horizons, these layers contained less organic matter than the topsoil in both CTRL and KVDS groups (Table 1A and 1B). This first measurement made in 2021 in dried soil samples inform about an Eh_{pH7} not influenced by the microbial activity. We can consider it like a zero point at the end of winter, influenced by the chemical composition of the soil and the environment. That is why the Eh_{pH7} of the KVDS soil richer in organic matter was more reduced than the CTRL soil.

The monthly measurements from spring of the Eh_{pH7} illustrate on the ability of the rhizosphere to evolve versus a more reduced environment, with the correction given by plant roots and microbial activities during the season. The first monthly measurements of the Eh_{pH7} redox potential in the orchard soils was conducted in 2023, starting when the soil temperature was above 15°C. The evolution of Eh_{pH7} allowed us to verify that all the orchard soils are oxidized in the KVDS and CTRL zones, with average values at 10 cm from 496 to 533 mV for the KVDS soils, and 466-522 mV for the CTRL group. All redox measurements at 25 cm illustrated higher oxidation in the soils than at 10 cm, with dispersed Eh_{pH7} from 539 to 566 mV for the KVDS group and from 506 to 558 mV for the CTRL group. So, the KVDS group soils are regularly more oxidized than the CTRL group soils (Table 1B). This indicator illustrates the capacity of the soil to maintain healthy root development, but it can also measure the impact of the roots which are more developed with the CTRL group, roots which can provide more exudates and balance the Eh/pH couple of the rhizosphere.

Agroecological orchard management is crucial for rectifying oxidized soil-plant systems, involving enriching soils with organic matter to establish stable porosity via enzymatic reactions and clay particle stabilization (Hassink, 1997; de Andrade Bonetti et al., 2017; Stegarescu et al., 2020). Increased soil organic matter enhances microbial biomass and overall enzyme activities (García-Gil et al., 2000). Application of compost, as seen in a kiwifruit orchard sensitive to KVDS, demonstrated positive results after three growing seasons (2020-2023), emphasizing the need for soil decompaction and immediate biomass addition for physicochemical correction (Bardi et al., 2020).

Our findings (Table 1A) suggest that higher clay content, reduced macroporosity and imbalanced cation exchange capacity (CEC) likely contributed to KVDS. Significantly lower macroporosity in 0-30 cm and 30-60 cm layers of KVDS soils (Table 1A), where kiwifruit roots concentrate, shows a potential correlation. In soil regeneration, the CEC is the reservoir of fertility and is closely linked to the soil given by the negative charges on the surface of clay and organic matter. The CEC is also an important factor in the soil for structuring microaggregates. According to the distribution of the cations, the clays will be more or less cohesive, creating micro-aggregates important for the structure of the soil. So, the impact of the two divalent cations Ca and Mg on the CEC in good proportions is very important on the structure of the soil and its porosity, its capacity to keep water (Mg) or to flocculate the micro-aggregates (Ca). The best air:water ratio in a soil is obtained with a ratio of 68:12% (Ca/Mg) on the CEC and with K at 4%, Na at 1,5%. Calcium and magnesium should occupy 80% of the CEC (in meq kg^{-1}). Here, in the KVDS and the CTRL zones of the orchard, the ratios are unbalanced: 78:19 in the KVDS and 80:15 in the CTRL (Table 1A); 80:15 in the KVDS and 79:16 in the CTRL (Table 1B). This unbalanced ratio of Ca/Mg on the CEC is an important factor of declining of the porosity of the soils in this orchard. Soil compaction has already been described and studied in other crops and there is a negative correlation between soil compaction and its water content. Compacted soil strata lose this compaction when they are wet and it was verified during the measurements during the wet days in May 2023, and on the contrary their compaction increases when their water content drops below a threshold to the point of encountering great difficulty in pushing the electrodes into the ground (Mondal and Chakraborty, 2023). Root pruning (Figure 1) stimulated healthy root release, facilitating regeneration after KVDS damage (data not shown)

The optimization of irrigation management resulted in the water saving of approx. 30% compared to the conventional management. Reducing the applied volume helped to increase soil aeration and create an optimal environment for root growth. Water table monitoring showed higher levels at the trial outset in October 2021, decreasing post-drainage system installation in the KVDS plot. The system effectively reduced water excess, enhancing undersoil water circulation in the KVDS area over two years. This relationship between rain and soil water table dynamics impacted the plant and soil health positively. In contrast, the CTRL plot, lacking drainage, exhibited continuous water movement, with small water table peaks only after heavy rain events.

Microscopy analysis revealed substantial damage to KVDS roots, including flaking and browning of the rhizodermis, decay of the central stele, and cortex detachment (Figure 4).

Plant status scoring (Figure 3) showed rapid canopy recovery in the first year (2021-2022), with a slower pace in the second year (2022-2023), likely because of the warm and dry 2022 summer. In the KVDS block, KVDS symptom severity decreased over time, with a considerable increase in healthy plants in 2022. Positive trends continued in 2023, although impacted by the warm 2022 summer (+46.1% of healthy plants measured at the end of the three-year trial).

Figure 4. (left column) Detachment of the cortex from the central stele in KVDS-symptomatic roots; (central column) rhizodermis in control (CTRL, above) and KVDS-symptomatic roots (KVDS, below); (right column) central stele in control (CTRL, above) and KVDS-symptomatic roots (KVDS, below).

CONCLUSIONS

Implementing sustainable agronomic practices, such as drainage system installation and optimization of irrigation management, soil decompaction through suitable cover crops, organic matter addition post-KVDS symptoms, and root pruning for root regeneration facilitation, has created a conducive environment for kiwifruit plant growth, resulting in improved physiological conditions. Our study shows that enhancing soil physicochemical conditions and correcting oxidized soils through sustainable agroecosystem management, both irrigation and soil management, positively impacts the physiological well-being of KVDS-symptomatic kiwifruit vines. Thus, adopting a sustainable and agroecological approach in kiwifruit orchard management emerges as a technically viable solution to curb the spread of KVDS by reinstating natural environmental conditions conducive to the thriving of kiwifruit plants.

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