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Research Papers

# Integrated management of citrus gummosis (*Phytophthora* spp.) in semi-arid Iran: combined effects of chemical, cultural, and nutritional strategies

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**Summary.** Citrus gummosis (citrus foot rot), commonly associated with *Phytophthora* spp. in citrus orchards, significantly limits citrus production in semi-arid regions, causing trunk cankers, gum exudation, and substantial yield losses. Field efficacy of an integrated disease management (IDM) programme combining chemical, cultural, and nutritional strategies was evaluated for reducing disease incidence and enhancing tree vigour and fruit yield. Over two years, trials were carried out across 12 commercial orchards. Cultural measures included soil aeration by collar excavation, conversion to dual-line drip irrigation, and application of well-decomposed organic manure as a surface mulch within the drip line. Assessments included disease incidence, severity of gum exudation, host plant vegetative growth, and fruit yields. Six months after implementation, disease incidence decreased from 65% at baseline to 20 ± 3% in the surviving IDM-treated trees, compared with 65 ± 5% in the untreated controls (GLMM treatment effect: $\chi^2(1) = 48.3$, $P < 0.001$). IDM-treated trees exhibited a 40% increase in shoot length and a 38% increase in trunk-diameter increment, while mean fruit yield increased from 15 ± 2 to 25 ± 3 kg tree$^{-1}$, corresponding to a 66.7% increase ($P < 0.001$). The IDM programme also improved tree recovery relative to the untreated controls in the semi-arid orchards evaluated. Although this IDM package gave short-term efficacy under the semi-arid conditions evaluated, its regional transferability should be validated through multi-location trials before broad implementation. Because *Phytophthora* pathogens were not isolated and identified, these results came from management of a macroscopic gummosis symptom complex, so long-term economic analyses and robust epidemiological monitoring are required to substantiate robust field recommendations.

**Keywords.** Soil waterlogging, orchard sanitation, fungicide management, tree recovery, soil aeration.

## INTRODUCTION

Citrus gummosis, caused primarily by the oomycete pathogens *Phytophthora nicotianae, P. citrophthora,* and *P. palmivora*, is among the most destructive diseases affecting citrus production, with particularly severe impacts in semi-arid regions (Hamdan *et al.,* 1995; Ippolito *et al.,* 2004; Hussain *et al*., 2025). The disease causes gum exudation from distinct citrus tree cortical lesions and trunk cankers, accompanied by longitudinal cracking and bark necroses, which gradually reduces tree vigour and fruit yields (Cacciola and Magnano di San Lio, 2008). Infected trees typically show initial symptoms at crown or collar regions, with necrotic lesions progressing upward to form extensive cankers that can lead to tree death if left unmanaged. The pathogens thrive under conditions of excessive soil moisture and poor aeration, where motile zoospores readily infect roots and the host collar regions. Irrigation management and soil drainage are therefore important determinants of disease incidence and severity. Yield losses attributed to citrus gummosis range from 10 to 30% in areas with environmental conditions favourable for pathogen survival and spread (Chaudhary *et al.,* 2016; Chaudhary *et al.,* 2020).

Growers have traditionally managed citrus gummosis by using resistant rootstocks, pruning infected bark tissues, improving soil drainage, and avoiding excessive irrigation, in addition to applying systemic fungicides such as metalaxyl and fosetyl-Al (Leoni and Ghini, 2006; Cacciola and Magnano di San Lio, 2008; Mekonen *et al.,* 2015). However, single-component disease management methods often fail because *Phytophthora* populations can rapidly develop fungicide resistance and maintain persistent soilborne inoculum (Bittner *et al.,* 2017; Massi *et al.,* 2021; Moreira *et al.,* 2023; Islam *et al.,* 2024). Integrated disease management (IDM), which combines chemical treatments with cultural and nutritional interventions, offers potential to reduce pathogen pressure and accelerate tree recovery (Razdan and Sabitha, 2009; Gilardi *et al.,* 2013; Lahlali *et al.,* 2024). For example, adding organic manure to soil enhances its structure and aeration, which reduces the survival of *Phytophthora* propagules (Kim *et al.,* 1997; Núñez-Zofío *et al.,* 2011; Farooq *et al.,* 2024). Likewise, foliar sprays of humic acid and calcium chelates can enhance tree vigour and increase resistance to stress conditions (Ramírez-Gil and Morales-Osorio, 2020; Ennab *et al.,* 2023; Amerian *et al.,* 2024).

Despite these advancements, few studies have evaluated integrated management programmes under the specific environmental conditions of semi-arid citrus production regions such as Jahrom and Qir in southern Iran, where high temperatures and irregular rainfall intensify disease impacts. Combined effects of fungicide applications, irrigation system modifications, trunk sanitation, and nutritional supplements also remain poorly documented for these agro-ecological zones (Rovetto *et al.,* 2024).

The present study was designed to test effectiveness of an integrated management strategy for citrus gummosis in commercial orchards of Jahrom and Qir. The programme combined systemic fungicides (metalaxyl and fosetyl-Al), soil and trunk sanitation, conversion from flood to drip irrigation, and foliar nutrition with humic acid–calcium chelate and amino acids. The study aimed to evaluate short-term efficacy of these control methods for reducing incidence and severity of gummosis, effects on plant growth and fruit yields, and as potentially sustainable disease management recommendations for semi-arid regions.

## MATERIALS AND METHODS

### *Study area and experimental layout*

This study was conducted during two consecutive citrus growing seasons (in 2023 and 2024), in twelve commercial orchards located in the Jahrom and Qir regions of southern Iran. The selected orchards had documented histories of high gummosis incidence (>60% of trees showing visible gum exudation on trunks). All trees were mature orchard trees, 15 to 20 years old, and were grafted on sour orange (*Citrus aurantium*) rootstock. Tree age within each orchard was uniform (±2 years), and no rooted cuttings were used. Although sour orange is historically classified as moderately tolerant of *Phytophthora* gummosis, this natural tolerance can be overwhelmed under sustained high disease pressure. The high gummosis incidence in the selected orchards occurred in the context of long-term flood irrigation and prolonged waterlogging at the plant collar regions, together with the absence of a previous specific disease-management programme.

Within each of the 12 orchards, four randomized replicate blocks were established; each block contained both an IDM-treated plot and an untreated control plot, consistent with the random-effects structure (orchard and block nested within orchard) used in the mixed models described below. Each treatment arm comprised five monitored trees per replicate block (five trees × four blocks = 20 trees per orchard per treatment), giving totals of 240 trees per treatment (control and IDM) across the 12 orchards (total = 480 trees). All trees were monitored for disease incidence, severity, vegetative growth, chlorophyll content, and yield.

### *Treatment description*

An integrated disease management strategy was assessed, combining chemical, cultural, and nutritional interventions.

*Chemical treatments.* Two targeted interventions were assessed: a soil-applied drench of mefenoxam (metalaxyl-M; Ridomil Gold SL®, 480 g a.i. $L^{-1}$; ≈1.75 g a.i. $L^{-1}$, as prepared), delivered through the dual-line drip irrigation system to ensure uniform distribution throughout the active root profile without mechanical root disturbance; or scheduled foliar applications of fosetyl-Al (Aliette® 80 WP; 2.0–2.5 g a.i. $L^{-1}$), applied to the tree canopies until runoff at 45 d intervals during peak infection periods. The two fungicides were not tank-mixed or applied simultaneously to individual trees. Surgical trunk wounds were protected only with a copper sulfate–lime (Bordeaux) paste (100 g $L^{-1}$), applied to collar regions and surrounding soil to suppress *Phytophthora* spp. infections.

*Cultural practices.* Cultural measures included tree collar excavation to keep trunk bases dry, carried out during the dry season (June to August), only for the IDM treatment. Experimental control trees remained undisturbed, representing standard local practice. Irrigation was converted from traditional flood irrigation to a dual-line drip system, with emitters displaced 75 cm from the trunk of each treated tree to prevent water from pooling in the excavated collar basin. Irrigation volumes and frequency were obtained from orchard records for both systems. Well-decomposed manure (20 kg per tree) was applied as surface mulch within the each irrigation drip line (i.e. not incorporated into the soil) to stimulate biological activity and improve soil structure without injuring shallow roots.

*Nutritional management.* Monthly foliar applications of a humic acid–calcium chelate solution (100 mL per tree) and amino acids (100 g per 100 L of water) were applied to improve plant vigour, nutrient uptake, and stress tolerance. For 2 years following these treatments, nitrogenous fertilizers were not applied to the soil, but nitrogen was applied only through foliar feeding, to minimize excessive vegetative growth and reduce susceptibility to gummoses.

*Sanitation measures.* Diseased bark tissues were carefully scraped away from trees with less than 30% collar circumference affected by gum exudation, using sterilized tools. To prevent the potential pathogen spread, all infected material was removed from the orchards. For trees with more than 30% of collar circumference infected, the trees were uprooted and removed from the orchard, to eliminate primary inoculum sources. To suppress residual soilborne propagules within canopy drip lines, the empty planting sites were drenched with a mefenoxam (metalaxyl-M) solution to a depth of 20 cm, with mefenoxam and fosetyl-Al never tank-mixed, and reflecting that fosetyl-Al requires systemic uptake through living plant tissue to be effective so is unsuitable for soil application to an unplanted site, in accordance with optimized application guidelines. Pruning tools were disinfected with 10% bleach. Wounds were immediately protected with a Bordeaux paste (copper sulfate–lime) or a copper-based dressing following label recommendations. Bleach was not applied directly to living bark.

All selected trees within each orchard were of uniform age (± 2 years) and of similar trunk diameters, to minimize host plant variability.

### *Data collection*

*Disease evaluations.* Disease incidence was recorded monthly as percentage of infected trees per replicate, and gum exudation severity classified using 0 to 5 scale, where 0 indicated no symptoms, and 5 indicated that >75% of the tree collar circumference was affected.

*Vegetative tree growth, leaf chlorophyll contents, and fruit yields.* Vegetative growth (annual shoot extension, trunk diameter increments), and leaf chlorophyll contents (SPAD index), were measured on five randomly selected trees per replicate (i.e., five trees × four replicates = 20 trees per orchard per treatment) across the 12 orchards). This gave 240 trees per treatment. Following removal of 47 infected IDM trees (see below), post-treatment vegetative-growth and yield values for the IDM group were based on the 193 surviving trees, while experimental control values remain based on all 240 control trees. These tree-level observations were used in the tree-level mixed-model analyses described below. Leaf chlorophyll content was measured using a portable SPAD-502 Plus chlorophyll meter (Konica Minolta Inc., Osaka, Japan), following the calibration framework of Markwell *et al.* (1995). Measurements were taken between 9:00 and 11:00 am each measurement day to minimize diurnal variations. For each tree, five mature, fully expanded, sun-exposed leaves were selected from current season growth, and three readings were taken per leaf (avoiding midribs). The arithmetic mean of all 15 readings (five leaves × three readings) was recorded as the SPAD value for each tree. Fruit yield was measured by counting fruits per tree, and recording total fruit weight (kg $tree^{-1}$) at harvest.

*Soil parameters*. Soil parameters were assessed monthly in a subset of experimental plots. These parameters included soil moisture content, duration of surface soil saturation (waterlogging) at tree collars, soil porosity measured using the core method, and biological activity assessed using assays for phosphatase and urease. Phosphatase activities were measured using p-nitrophenyl phosphate substrate (Tabatabai and Bremner, 1969). Urease activities were measured using the indophenol blue method (Kandeler and Gerber, 1988).

### *Statistical analysis of data*

All analyses were carried out using R v4.3. For continuous response variables (shoot length, trunk increment, fruit weight, enzymatic activities) linear mixed-effects models were fitted using lmer (package lme4) with the fixed effects treatment, year, and their interaction, and with random intercepts for orchard and for block nested within orchard, plus a random intercept for tree to account for repeated measurements on the same tree: lmer(response ~ treatment * year + (1|orchard) + (1|orchard:block) + (1|orchard:block:tree)). For binomial response data (tree-level disease incidence) generalized linear mixed models were fitted with a logit link, using glmer and the same random structure. Denominator degrees of freedom and *P* values for LMMs were estimated using the Satterthwaite approximation implemented in lmerTest. Likelihood-ratio tests ($\chi^2$, df), and, where appropriate, Wald Z statistics, are reported for GLMMs.

### *Pathogen identification – a methodological limitation*

Isolations and identification of *Phytophthora* species from infected tissues or soil were not carried out at the onset of this study, due to practical limitations in field sample handling and laboratory capacity at the time. Therefore, while observed symptoms (gum exudation, trunk cankers, root necroses) resembled those caused by *Phytophthora* species (Cacciola and Magnano di San Lio, 2008), the causal agent(s) could not be confirmed in the surveyed orchards. This omission is mitigated by prior peer-reviewed surveys that have confirmed the presence of *P. nicotianae* and *P. citrophthora* as the dominant citrus gummosis pathogens in semi-arid Middle Eastern and Mediterranean citrus-growing regions comparable to Jahrom and Qir (Hamdan *et al.,* 1995; Cacciola and Magnano di San Lio, 2008). This indicates the regional likelihood of *Phytophthora* etiology. Consequently, the present study results describe the management of "citrus gummosis syndrome" rather than disease caused by confirmed *Phytophthora* species. The authors acknowledge that this as a significant limitation in the present study (see Discussion).

## RESULTS

### *Disease incidence and severity*

During two consecutive growing seasons (in 2023 and 2024), the integrated management strategy reduced incidence and severity of citrus gummosis across all the 12 orchards studied (Table 1; Figure 1). At baseline (month 0, prior to any interventions), disease incidence among the 15 to 20-year-old assessed trees did not differ between the two groups (controls: mean = 65 ± 5%; IDM =65 ± 4%; n = 240 trees per treatment), confirming that both groups began in the experiments from equivalent disease levels. Within the IDM group, 47 of the 240 enrolled trees (19.6%) subsequently exceeded the

**Table 1.** Mean disease gummosis incidence proportions (%) and severity scores for citrus trees in orchards either maintained without treatment (Control), or where integrated disease management was applied, during 2023 and 2024.

| Season | Parameter | Control | Integrated Management | Reduction (%) | *P*-value |
|---|---|---|---|---|---|
| 2023 (6 months) | Disease incidence (%) | 65 ± 5 | 20 ± 3 | 69.2 | < 0.01 |
| 2024 (12 months) | Disease incidence (%) | 66 ± 4 | 18 ± 2 | 72.7 | < 0.01 |
| 2023 (6 months) | Severity (0 to 5 scale) | 3.8 ± 0.2 | 1.1 ± 0.1 | 71.1 | < 0.01 |
| 2024 (12 months) | Severity (0 to 5 scale) | 3.9 ± 0.3 | 1.2 ± 0.1 | 69.2 | < 0.01 |

Data are presented as orchard-level means ± SE (n = 12 orchards). For tree-level analyses, 240 trees per treatment (control and IDM) were enrolled at baseline across the 12 orchards, consistent with the number reported in Table 2; this n is reported consistently in all tables and text.

A total of 47 of the 240 IDM trees (19.6%) exceeded the >30% collar infection threshold, and were uprooted and removed during this study; the 2024 (12-month) IDM values in this table are therefore based on the 193 surviving IDM trees, while control values remain based on all 240 control trees (no removals occurred in the untreated control).

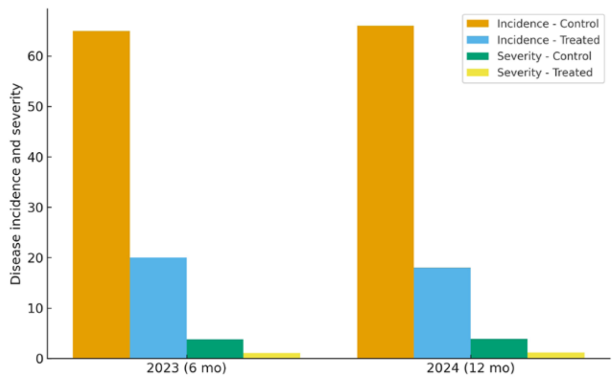


**Figure 1.** Graphical representation of the decline in disease incidence and severity in 12 citrus orchards following the integrated disease management (IDM) treatment used in this study.

predefined 30% collar-circumference infection threshold (see below), and were uprooted and removed. The remaining 193 IDM trees (80.4%) each had <30% collar involvement, underwent bark sanitation treatments, and were retained for all following assessments. Because the removed trees were, by definition, the most severely diseased, their exclusion is conservative with respect to the reported treatment effects, and likely underestimates true disease pressure that would have persisted in the IDM group without removal. No removals were carried out in the untreated control groups (n = 240 throughout). Consistent with this design, disease incidence declined significantly from the 65% baseline to 20 ± 3% at 6 months and 18 ± 2% at 12 months in the surviving IDM trees, compared with a stable 65 to 66% in the control (GLMM treatment effect: $\chi^2(1) = 48.3$, $P < 0.001$; Table 1). Severity of gum exudation, rated on the 0 to 5 scale, declined significantly from a baseline mean of 3.8 ± 0.2 (moderate-to-severe symptoms) to 1.1 ± 0.1 (mild symptoms) at 6 months (LMM treatment effect: $F_{1,22} = 41.2$, $P < 0.001$), reflecting substantial improvements in tree health. Consistent with prior research, the overall reduction in disease pressure observed here is best interpreted as a combined effect of the full IDM package (systemic fungicides, collar excavation, improved drainage via drip irrigation, manure mulching, and wound sanitation) rather than from fungicide applications alone.

### *Vegetative growth*

Statistically significant improvements in vegetative growth parameters were recorded in the IDM-treated trees compared with untreated controls (Table 2). Mean shoot lengths increased by 40% (from 55 cm to 77 cm), and mean trunk diameters increased by 38% (from 8 mm $yr^{-1}$ to 11 mm $yr^{-1}$). Leaf chlorophyll content, measured via SPAD readings, increased by 25%, indicating greater relative leaf greenness and consistent with improved tree physiological status.

### *Fruit yields, and soil physical properties and aeration dynamics*

Integrated management increased fruit yields, and enhanced soil enzyme activity (Table 3). Mean fruit yields were 15 ± 2 kg $tree^{-1}$ from the control trees, and 25 ± 3 kg $tree^{-1}$ from the IDM treatments, a mean difference of 10.0 kg $tree^{-1}$ (95% CI: 6.2–13.8 kg; $P < 0.001$) estimated from the mixed model contrasts (95% CI, calculated via emmeans). Soil phosphatase activity increased by 45%, and urease activity by 32% for the IDM treatments, indicating enhanced biological activity and nutrient cycling capacity in the tree rhizospheres from these treatments.

The IDM approach also improved soil physical conditions around the tree collar zones (Table 4). Rather than reducing overall soil water contents, which addition of organic manure and conversion to drip irrigation would be expected to increase, the IDM interventions reduced the duration of surface soil saturation (waterlogging) at the tree collars by 35%, consistent with reduced water pooling under the drip-irrigation

**Table 2.** Mean vegetative growth parameters of citrus trees receiving integrated disease management (IDM) or remaining untreated.

| Parameter | Control | IDM treated | Change (%) | *P*-value |
|---|---|---|---|---|
| Shoot length (cm) | 55 ± 3 | 77 ± 4 | +40 | < 0.01 |
| Trunk diameter increment (mm $yr^{-1}$) | 8.0 ± 0.6 | 11.0 ± 0.8 | +38 | < 0.01 |
| Leaf chlorophyll (SPAD) | 42 ± 2 | 52 ± 2 | +25 | < 0.05 |

Values are means ± SE. Baseline enrollment was 20 trees per orchard × 12 orchards = 240 trees per treatment. Control values are based on all 240 control trees (no removals). Treated (IDM) post-treatment values are based on the 193 IDM trees surviving after removal of the 47 trees that exceeded the 30% collar-infection threshold. The reduction in n is accounted for in tree-level mixed models, which accommodated unbalanced group sizes.

**Table 3.** Mean citrus fruit yields and soil biological activities for control and integrated disease management trees.

| Parameter | Control | Integrated Management | Improvement (%) | *P*-value |
|---|---|---|---|---|
| Mean fruit yield (kg tree$^{-1}$) | 15 ± 2 | 25 ± 3 | +66.7 | < 0.001 |
| Mean phosphatase activity (μmol P g$^{-1}$ h$^{-1}$) | 100 ± 8 | 145 ± 10 | +45 | < 0.05 |
| Mean urease activity (μmol $NH_4^+$ g$^{-1}$ h$^{-1}$) | 120 ± 9 | 158 ± 11 | +32 | < 0.05 |

**Table 4.** Mean soil physical conditions near citrus plant collar zones for untreated (Control) plants, and those treated with integrated disease management (IDM).

| Parameter | Control | IDM treated | Change (%) | *P*-value |
|---|---|---|---|---|
| Surface saturation / waterlogging duration at tree collars (% of monitoring days) | 28 ± 3 | 18 ± 2 | –35 | < 0.01 |
| Soil porosity (0–30 cm) | 42 ± 2 | 50 ± 3 | +19 | < 0.05 |

system. This reduced saturation window reduces the favourable environment for *Phytophthora* spp. survival and infection. Meanwhile, soil porosity in the 0–30 cm layer increased by 19% following the integrated management intervention, consistent with improved soil aeration and drainage.

### *Efficacy of sanitation practices*

Of the 193 IDM trees with <30% collar circumference affected by gummoses that underwent careful bark removal, all recovered fully within 4 weeks, with no further spread of symptoms. In contrast, the 47 trees exhibiting >30% collar involvement were removed according to the predefined management protocol; these observations do not independently validate the 30% threshold. Application of protective copper sulfate–lime paste to treated wounds prevented re-infection in 185 of the 193 sanitized trees (95.9%; 95% CI: 92.3–98.0%) during the 18 month monitoring period.

## DISCUSSION

This study has demonstrated the effectiveness of integrated disease management (IDM) for mitigating citrus gummosis, likely associated with *Phytophthora* species under semi-arid conditions in southern Iran. The combined use of systemic fungicides, cultural practices, soil amendments, and host nutritional strategies was associated with reduced disease pressure, improved tree health, and enhanced fruit yields. As discussed below, however, because the IDM package was evaluated only against an untreated control, and pathogen identifications were not carried out, these results should be interpreted as preliminary evidence for the management package, rather than as proof of mechanism or independent contribution of any single component (see Limitations).

The reductions in disease incidence and severity observed in this study corroborate previous results for the curative and protective effects of systemic fungicides, such as metalaxyl and fosetyl-Al, against *Phytophthora* infections in citrus. In the semi-arid calcareous soils of southern Iran, fosetyl-Al was applied at 45 d intervals according to label guidance. The present study did not measure fungicide persistence or residual activities. Nonetheless, the risk of pathogen resistance to fungicides, particularly to metalaxyl/mefenoxam, remains a concern and warrants ongoing monitoring in long-term disease management programmes (Davidse *et al.,* 1983).

Reduced waterlogging duration at the tree collars probably suppressed *Phytophthora* proliferation, because zoospore movement depends on free water (Chaudhary *et al.,* 2016). These results support previous studies that have demonstrated that physical interventions, such as collar excavation and improved drainage, can help reduce soilborne diseases (Shrivastava and Kumar, 2015; Bhatt and Sharma, 2020; Brasier *et al.,* 2022; Fadli *et al.,* 2022; Sapkota *et al.,* 2023).

Soil amendments, including surface mulching with decomposed animal manure, improved soil physical properties such as porosity (+19%; Table 4) and were associated with increased enzyme activity, indicating enhanced biological activity and nutrient cycling capacity (Klein *et al.,* 2012). These improvements are consistent with mechanisms that may enhance soil suppressiveness (e.g., increased porosity, enzyme activities), but direct evidence – for example, quantification of *Phytophthora* soil inoculum or microbiome analyses – was not collected in this study; soil suppressiveness therefore remains inferred rather than demonstrated, and should be confirmed by targeted pathogen-population monitoring conducted monthly for at least 24 months to cover two full citrus growing seasons and capture seasonal variation in disease pressure.

Foliar nutrition — monthly applications of humic acid–calcium chelate and amino acids (Section 2.2) — enhanced vegetative growth and chlorophyll content, underscoring the role of foliar biostimulants in improving plant metabolism, nutrient assimilation, and stress tolerance (da Silva *et al.,* 2021; de Moura *et al.,* 2023). Because these products were applied to the canopy rather than the soil in this study, we interpret their contribution as acting through plant physiology rather than through direct modulation of the soil microbiota; these physiological enhancements likely contributed indirectly to disease suppression by boosting overall tree vigor and increasing the capacity to withstand pathogen attack.

Sanitation of bark lesions and protective wound treatment proved highly effective in preventing reinfection, supporting the 30% collar-circumference threshold used to distinguish sanitation from removal in this study. This finding aligns with integrated management principles emphasizing timely wound treatment to disrupt pathogen entry and limit inoculum spread (Hajji-Hedfi *et al.,* 2024). Trees exceeding this threshold exhibited poor recovery, supporting its use as a removal criterion, in line with recommendations for managing *Phytophthora* trunk infection (Fadli *et al.,* 2022).

The integrated approach markedly enhanced fruit yield relative to what would be expected from single-method interventions reported elsewhere. The concurrent application of chemical, cultural, and nutritional practices underscores the potential value of integrated strategies in plant disease management, particularly in regions challenged by water scarcity and persistent pathogens.

This study highlights that, in semi-arid environments, reducing waterlogging at the collar and improving root-zone aeration are critical components of effective citrus gummosis management. Integrating multiple management tactics reduces pathogen pressure and enhances tree resilience while promoting sustainable production practices.

While the results are promising, further long-term studies are essential to evaluate the sustainability of IDM strategies, particularly concerning potential fungicide resistance, optimization of organic amendment protocols, and economic feasibility for commercial growers. Cost–benefit analyses and region-specific adaptations will be crucial for the widespread adoption of these integrated practices.

*Limitations*

Two methodological limitations of this study should be highlighted. First, the IDM package was compared only to an untreated control. The observed effects therefore represent the combined outcome of multiple simultaneous interventions – (i) the shift from flood to drip irrigation, (ii) the change from soil to foliar fertilization, (iii) manure mulching, (iv) trunk surgery and sanitation, and (v) fungicide applications – and our design does not allow us to quantify the independent contribution of each component to disease suppression or yield improvement. We did not quantify pathogen population density in soil before or after the intervention, so mechanisms such as "soil suppressiveness" remain inferred rather than demonstrated. Future studies should use factorial or other appropriately structured multi-treatment designs that separately manipulate the major cultural, chemical, nutritional, and sanitation components, allowing their individual and interaction effects to be estimated.

Second, we did not perform molecular or cultural confirmation of *Phytophthora* species at the onset of the study (Section 2.5). While the symptoms were typical of *P. nicotianae* or *P. citrophthora* – the dominant species reported in semi-arid citrus orchards of the wider region (Hamdan *et al.,* 1995; Cacciola and Magnano di San Lio, 2008) – we cannot rule out the involvement of other *Phytophthora* species or other oomycete pathogens. This uncertainty means our IDM package may have been effective against a pathogen complex, not necessarily *P. nicotianae* alone. Future studies must include species-level identification (via PCR or sequencing) before and after intervention to establish a causal link between management practices and specific pathogen suppression.

In conclusion, over the two seasons of this trial the integrated management strategy reduced disease incidence and improved tree health and productivity under the specific environmental conditions of the studied orchards. Extrapolation to broader claims of robustness and sustainability across other semi-arid regions requires replicated multi-year trials, pathogen population monitoring, and formal cost–benefit analyses (economic analysis horizon ≥ 5 years). The IDM model presented here provides a practical starting framework for managing citrus gummosis under the semi-arid orchard conditions evaluated, pending this further validation.

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