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Feature Article

Integrated Pest Management Strategies for Strawberry Production in Taiwan: A Review of Technological Innovations and Implementation Challenges

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Abstract

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Strawberry is a highly valuable economic crop with a domestic cultivation area of approximately 586 ha, primarily concentrated in Miaoli County. During the strawberry production season, a large number of tourists are attracted, which drives the development of the surrounding industries. Over the past decade, the strawberry industry has faced increasing challenges, including threats from diseases and pests, varietal transitions, and climate change, making cultivation progressively more difficult. Based on the principle of integrated pest management (IPM), which emphasizes prevention over treatment, our research team has implemented the following research and extension strategies tailored to different cultivation stages: (1) Establish a strawberry healthy runner plant supply chain by developing diagnostic techniques for key pathogens and integrating these into the voluntary pathogen-free certification system for strawberry propagation, while guiding the industry toward specialized nursery production and propagation; (2) Develope a screening platform to assess the resistance and susceptibility of domestic strawberry germplasm to manage major diseases, by integrating molecular marker-assisted breeding and high-throughput phenotyping technologies to reduce the reliance on extensive field selection and accelerate the breeding process; (3) Adapt nursery propagation and fruit production management strategies to mitigate the impact of high temperatures on strawberry production due to climate change; (4) Provide technical guidance to farmers on pre-planting soil disinfestation, optimizing base fertilizer according to soil analysis data, and implementing rationalized liquid fertilizer application after transplanting; (5) Collaborate with interdisciplinary teams to develop machine learning and deep learning algorithms for the automated identification of strawberry diseases and pests while integrating an expert decision support system to enable real-time and accurate diagnosis and management recommendations for farmers. Through the promotion of IPM strategies, strawberry yield and quality will be gradually improved, increasing

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farmer profitability and creating an environmentally friendly approach while meeting consumer market demand.

Key words: Healthy runner plants, Disease-resistant breeding, Climate change, Soil disinfestation, Deep learning.

INTRODUCTION

Strawberry (*Fragaria ×ananassa*) is highly favored by consumers due to excellent taste, attractive appearance, and rich nutritional value. The domestic strawberry cultivation area in Taiwan is approximately 586 ha, with Miaoli County accounting for 90%, making it the most important production area. After integrating with agritourism, it has become a highly representative sixth-level industry. However, according to the annual pesticide residue monitoring reports on fruit and agricultural products published by the Ministry of Agriculture (MOA), strawberry has ranked first in pesticide residue detection rates for consecutive years, making this issue a major consumer concern. To enhance food safety in agricultural products, MOA has been actively promoting a policy to halve chemical pesticide risks within ten years, with integrated pest management (IPM) as the core promotional strategy. IPM refers to a comprehensive approach to managing crop pests by integrating multiple control methods to address single or multiple pest issues. Chemical pesticides are used only when necessary, emphasizing a prevention-first approach with chemical control as a supplementary measure (Stenberg 2017).

Approximately 29.25 million strawberry runner plants are required annually, with the propagation period occurring from April to September. However, the greatest challenge during the runner plant propagation period is disease management, particularly the occurrence of anthracnose rot during the high-temperature and rainy months of July and August. Since 2010, the industry has faced severe runner plants shortages due to anthracnose rot (Chung *et al*. 2020). Most of the current runner plant propagation methods still rely on farmers cultivating strawberry runner plants in open-field environments with overhead irrigation, and it is also unknown whether the mother plants are infected with the pathogen, resulting in serious latent infections of anthracnose rot. Starting in 2018, the main strawberry cultivar in the production area gradually shifted from 'Taoyuan No. 1' to 'Xiang-Shui', and by 2019, the planting area of 'Xiang-Shui' rapidly increased to approximately 80%. Because 'Xiang-Shui' is highly susceptible to leaf blight, this varietal transition has caused leaf blight to emerge as a significant disease (Chung *et al*. 2021; Wu *et al*. 2021). Anthracnose rot has the characteristic of latent infection (Prusky 1996), while leaf blight has not yet been confirmed to be capable of latent infection. However, both diseases can be transmitted through asymptomatic runner plants or mother plants with rainfall and irrigation water contributing to the splash dispersal of conidia (Chung *et al*. 2022; Alam *et al*. 2024). The high temperature and intermittent heavy rains during the monsoon and typhoon seasons create environmental conditions conducive to infectious disease and epidemics, causing farmers to apply fungicides more frequently. If infected plants are not thoroughly removed during the runner plants propagation period, large-scale disease outbreaks often occur after transplanting, ultimately leading to wilting and plant death. In 2015, after strawberry transplanting, several fields in Dahu Township and Shitan Township experienced a replanting rate of up to 30%. In addition to anthracnose rot caused by pathogen-infected runner plants, the high incidence of disease in some fields may have resulted from the accumulation of *Fusarium oxysporum* f. sp. *fragariae* (Chung & Wu 2017). According to estimates from the Dahu Area Farmers' Association in 2023, the yield reduction due to Fusarium wilt in the entire township was approximately 10–20%. Similar situations were observed in neighboring strawberry production

areas. On-site field assessments revealed that the causes of Fusarium wilt could be attributed to several factors, including pathogens that were latently infected in the runner plants or residues in the soil, early planting (from mid-September to early October) during high temperatures, improper water management after transplanting, and excessive fertilization. The damage rate of Fusarium wilt ranged from 30–90%, and compared to 2015, there was an additional factor of varietal change, from 'Taoyuan No. 1' to 'Xiang-Shui' (unpublished data).

In order to address the issue of frequent fungicide usage during strawberry runner plants propagation (Chung *et al*. 2022), and to reduce the usage of chemical pesticides during fruit production, our research team has implemented an IPM strategy, including the establishment of disease identification techniques for rapid confirmation of pathogen species, allowing for the development of targeted control strategies to minimize unnecessary fungicide usage by farmers. We have also guided farmers to gradually change their propagation methods, promoting a healthy runner plant propagation system; adaptive cultivation management strategies have been implemented to mitigate the impact of adverse conditions of climate change on strawberry, such as heat stress during the propagation period or early transplanting stages, which could lead to heat-related disorders or accelerated Fusarium wilt. Soil disinfestation and rationalized fertilization are conducted in the fields before runner plant transplanting, while natural enemies are released at appropriate timing during the fruiting period to control small pests. Our IPM strategy involves guiding farmers to reduce the frequency and amount of chemical pesticide usage, while ensuring economic benefits for farmers and promoting environmental sustainability, to produce high-quality and safe strawberry (Birch *et al*. 2011; Dara 2019; Huang *et al*. 2022; Angon *et al*. 2023). This review focuses on the current status of the strawberry industry in Taiwan, addressing field issues by applying established or developing IPM strategy. It also compiles relevant IPM technology from major strawberry-producing countries to inform future research and practical implementation.

STRAWBERRY IPM IMPLEMENTATION STRATEGY

Disease challenges in subtropical strawberry systems

The proportion of propagated strawberry runner plants by farmers remains above 70%, relying mostly on asexual propagation from mother plants retained in fruiting fields and cultivated in open-field environments in Taiwan. Anthracnose rot, leaf blight, Fusarium wilt, and angular leaf spot are the primary diseases causing large-scale runner plants wilt and mortality during the propagation stage or resulting in replanting rates exceeding 50% after transplanting. Therefore, the foundation of strawberry IPM must begin with healthy runner plants.

Anthracnose rot

Anthracnose rot is one of the most devastating diseases in the strawberry industry, causing severe economic losses. Initially, infected leaves develop dark brown spots that gradually expand; lesions on petioles and runners become sunken, and salmon to red conidial masses could be observed under high humidity. When the crown is infected, the aerial parts of the plant exhibit wilting symptoms, often leading to replanting rates exceeding 30–40% after transplanting (Chung *et al*. 2019). Multilocus sequence analysis coupled with morphological characterization identified five *Colletotrichum* species associated with strawberry anthracnose rot in Taiwan, including *Colletotrichum siamense* and *C. fructicola* (*C. gloeosporioides* species complex), *C. boninense* and *C. karstii* (*C. boninense* species complex), and a newly identified species, *C. miaoliense* (*C. acutatum* species complex) (Chung *et al*. 2020). Additionally, *C. siamense* is the predominant species isolated from major strawberry production areas in Taiwan. Mycelial

growth rate assessment at different temperatures indicates that its optimal growth temperature is approximately 27.9℃, in accordance with the observation that strawberry anthracnose rot is prevalent under high temperature and humid conditions in Taiwan. However, after transplanting in the fields, as the temperature significantly drops in December, the incidence of anthracnose rot also declines accordingly. Due to the common practice of open-field sprinkler irrigation for runner plants propagation and the lack of healthy mother plants, the incidence of latent infection by *C. siamense* has become increasingly severe.

Leaf blight

Phylogenetic analysis confirmed *Neopestalotiopsis rosae* as the primary pathogen causing strawberry leaf blight (Wu *et al*. 2021). In the field, the pathogen primarily infects leaves, crowns, petioles, runners, fruits, and roots of strawberry. Symptoms on leaves appear as nearly circular, elliptical, or elongated brown lesions with concentric rings, and black conidial masses are visible in the lesion center. When the crown is infected, affected leaves develop reddish-brown to purplish-brown interveinal discoloration covering one-third to two-thirds of the leaf area. Occasionally, small light brown to white spots resembling sunburn symptoms appear, and on the abaxial surface, net-like sunken brown lesions can be observed. Infected plants exhibit dwarfing, poor development of new leaves, reduced runner production, and decreased flowering and fruiting. Under severe infections, extensive leaf wilting and plant death may occur (Lai & Wu 2024). As the dominant cultivar has shifted from 'Taoyuan No. 1' to 'Xiang-Shui,' the incidence of leaf blight has significantly increased.

Fusarium wilt

Fusarium oxysporum f. sp. *fragariae*, the pathogen of Fusarium wilt, invades the plant and causes vascular occlusion, leading to functional loss and asymmetrical growth of the trifoliate leaves (Chung & Wu 2017; Pastrana *et al*. 2019). The development of malformed leaves often results in one-sided wilting, loss of leaf luster, crown and root discoloration, and root rot. Infected plants gradually weaken, shrink in size, and eventually wilt, making this a relatively slow-progressing disease. *F. oxysporum* f. sp. *fragariae* is a strawberry-specific forma species infecting only strawberries and not other crops such as cucumber, tomato, or eggplant. The disease can develop between 18–25℃, with an optimal growth temperature for the pathogen at 28℃, and higher temperatures accelerate disease progression (Chen *et al*. 2017). Additionally, this disease can persist in the soil for several years through chlamydospores, making it necessary to remove infected plant residues and conduct soil disinfestation to prevent recurring outbreaks.

Angular leaf spot

The primary pathogen causing strawberry angular leaf spot has been identified as *Xanthomonas fragariae* through phylogenetic analysis (Wu *et al*. 2020). The disease is spread via dew, rain, or overhead irrigation. High environmental humidity or the presence of leaf wounds increases the likelihood of infection. Infected leaves eventually wilt and remain in the soil or substrate, potentially serving as the initial inoculum source for the following season. Field observations indicate that the pathogen can currently infect most cultivated strawberry cultivars. *X. fragariae* can infect leaves, petioles, crowns, roots, sepals, and fruits, with the most prominent symptoms observed on leaves. The disease initially appears as water-soaked angular lesions restricted by leaf veins on the abaxial surface. When viewed under light or transmitted light, the lesions appear translucent. As the disease progresses, lesions turn from translucent to reddish-brown, sometimes with yellow margins, and in severe cases, lesions expand and coalesce, leading to complete leaf necrosis. Under high humidity, milky white to pale yellow bacterial exudates may form on the lesion surface. When sepals are infected, water-soaked angular symptoms also develop. Infected fruits exhibit yellowish and hardened flesh near the

attachment point to the sepals, rendering them unmarketable. An appropriate preventive strategy is to avoid planting runner plants infected with this disease.

Technological advances in IPM

Establishing a strawberry healthy runner plant supply chain

Use of healthy runner plants is the essential first step in strawberry IPM. To ensure that propagated runner plants are free from specific pathogens, countries such as the United States and Japan have established disease inspection standards and certification programs. In response to the demand for healthy runner plants, relevant regulations have been implemented, and the supply chain for healthy runner plants is being developed through collaboration between industry, government, academia, and research institutions in Taiwan.

1. Progress and applications of healthy runner plants propagation in Taiwan and other countries

California has the largest strawberry production area in the United States, and with a well-developed healthy strawberry runner plant propagation system that local farmers recognize for its benefits. In California, strawberry cultivars are developed by the Department of Plant Sciences at the Davis campus of the University of California (UC Davis), patented and licensed by UC Davis Technology Transfer Services, and maintained and distributed by Foundation Plant Services (FPS) (http://fps.ucdavis.edu). Additionally, the FPS is responsible for maintaining and distributing these cultivars. The nursery system consists of Foundation plants, Registered plants, and Certified plants. Foundation plants are the initial, pathogen-tested, true-to-type stock, from which Registered plants are clonally propagated under controlled conditions. Registered plants serve as the source material for mass-produced Certified plants intended for commercial fruit production. Throughout the process, strict health and varietal purity standards are maintained. Furthermore, the sale of runner plants requires pre-ordering in the previous year to facilitate nursery propagation planning.

Tochigi Prefecture is the largest strawberry producing area in Japan. It has more than 600 ha of strawberry cultivation, and the strawberry healthy runner plants propagation system has been implemented for decades. At present, 100% of farmers used the runners propagated following the healthy runner plants supply system. Most of the new cultivars released from Tochigi Prefecture are virus-free through tissue culture to obtain the nuclear stock. The plants of the nuclear stock in the provenance greenhouse are virus-free, and then the original stock is propagated from the nuclear stock. Plants propagated from the original stock are moved to the original nursery for cultivation, and these are the mother plants subsequently provided to farmers. Runners propagated from the mother plants in the nurseries are used for transplanting into the field (Ishikawa 2011).

To prevent the spread of diseases and improve the health of runner plants produced by strawberry nurseries, the MOA in Taiwan has established a voluntary pathogen-free certification system for strawberry propagation in 2018 (Chung *et al*. 2022). The propagation of strawberry runner plants is divided into several stages: G0, which refers to tissue culture plantlets; G1, which is tissue culture plants that have been acclimatized in a controlled facility environment; G2, which is progeny plants derived from G1 plants, also propagated in regulated conditions and used for further propagation; and G3, which is G2 plants propagated under regulated conditions and used for transplanting into the production field. The environmental conditions and management practices required for the propagation of each stage are based on established guidelines, including elevated beds 40 cm above the ground, specific mesh sizes for insect nets at each stage, and the use of sterilized cultivation media and water sources. Notably, to maintain the quality

of runner plants, it is crucial that no pathogens such as anthracnose rot (*Colletotrichum* spp.), Fusarium wilt (*Fusarium oxysporum* f. sp. *fragariae*), Strawberry mild yellow edge virus, or root lesion nematodes (*Pratylenchus* spp.) can be detected at any stage. Verified cultivars of runner plants are propagated, including 'Taoyuan No. 1', 'Xiang-Shui', 'Tainung No.1', 'Changzhi No.1', 'Changzhi No. 2', and 'Yuantu No.1' in 2024.

For the demand of healthy runner plants, in addition to certified runner plants propagated following the voluntary pathogen-free certification system, non-certified high-quality runner plants propagated from tissue culture mother plants have also been introduced as an initial production type by nurseries. These non-certified plants will be gradually incorporated into the certification system based on production capacity. For the main cultivar 'Xiang-Shui' in major production areas, a total of 38,440 G1-stage runner plants were produced by nurseries in 2024, of which approximately 8,040 were certified plants. These certified plants were primarily purchased by farmers for use as mother plants to propagate additional runner plants. At the G3 stage, 215,000 runner plants were propagated and directly supplied to farmers for field planting.

The complete three-stage propagation system has not yet been fully implemented in Taiwan, primarily due to several factors, including the delayed production of G0 plantlets, the high labor demand during the G1 production process, and the limited space, which requires waiting for seedlings of other crops to be cleared before acclimatization can take place. These constraints result in delayed G1 availability, subsequently compressing the time for G2 and G3 runner propagation. In recent years, adverse climatic conditions and disease outbreaks have significantly impacted strawberry production. Several nursery operators have expressed interest in propagating healthy strawberry runner plants, leveraging their existing tissue culture propagation technology, along with well-equipped facilities such as greenhouses, soil and water sterilization systems. As a result, the quantities of healthy strawberry runner plants are expected to increase annually.

2. Development of detection methods for anthracnose rot and Fusarium wilt

To establish a propagation and supply chain for healthy strawberry runner plants, key diseases such as anthracnose rot and Fusarium wilt are detected at different propagation stages. During strawberry runner plants propagation, while mother plant is latently infected with anthracnose rot, the disease could spread to runner plants through rainwater or irrigation splash. The detection methods for anthracnose rot latent infection could be categorized into two major types: culture-based methods and polymerase chain reaction (PCR)-based molecular detection methods. Culture-based methods include the Paraquat method, the freezing method, and the SDEI (simple diagnosis by ethanol immersion) method (Cerkauskas 1988; Ishikawa 2003; Mertely & Legard 2004). The advantages of these methods are their simplicity and low cost, making them easier for farmers or nursery operators to implement. However, these methods require a longer time (typically 3–10 d) to obtain results and rely on spore morphology for pathogen identification. In contrast, the molecular detection methods offer high specificity and low detection limits, facilitating internal quality control for nurseries while significantly reducing the time required for detection compared to culture-based methods. The disadvantages include relatively high costs and the necessity for laboratory testing. Several molecular detection methods, including PCR, nested PCR, quantitative real-time PCR (qPCR), high-resolution melting analysis (HRM), and loop-mediated isothermal amplification (LAMP) (Freeman *et al*. 2001; Perez-Hernandez *et al*. 2008; Debode *et al*. 2009; Zhang *et al*. 2016; Rahman *et al*. 2019), have been applied for pathogen detection in strawberry. In recent years, we developed a nested PCR detection method capable of detecting the primary

pathogens *C. siamense* and *C. fructicola* (Chung *et al*. 2022), and it has been successfully applied to the voluntary pathogen-free certification system in Taiwan. Additionally, to facilitate on-site detection in fields or nurseries, a portable plant disease rapid screening kit has also been developed. Using a non-powered nucleic acid extraction kit, nucleic acids are extracted and then amplified via the LAMP method. Indicator dye (hydroxynaphthol blue, HNB) is added for visual interpretation of results, allowing on-site testing and result determination (Hung *et al*. 2024).

Infected strawberry mother plants with Fusarium wilt could transmit the pathogen to runner plants through the vascular bundles via stolons. To confirm that the mother plants used for propagation are free from this pathogen, selective culture medium FoG1 is employed for culturing (Nishimura 2007; Chung *et al*. 2018). If purple-red colonies appear, it is determined that the tested mother plant may carry the pathogen of Fusarium wilt and should not be used as a propagation source. Additionally, the application of multiplex PCR would assist in the screening of mother plants and the detection of residual soil pathogens (Suga *et al*. 2013). LAMP detection technology has also been developed in recent years and applied for screening strawberry germplasm preserved at Tochigi Prefecture Strawberry Research Institute in Japan (Katoh *et al*. 2021).

3. Development of detection methods for leaf blight and angular leaf spot

Molecular detection methods for strawberry leaf blight currently include HRM (Rebello *et al*. 2023) and polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) (Kaur *et al*. 2022). Primers targeting ITS, *TUB*, and *TEF* of strawberry leaf blight were designed in 2024 by our research team, and a nested PCR method was developed, with a detection limit of 100 fg of *Neopestalotiopsis rosae* DNA (Lai & Wu 2024).

The detection methods for strawberry angular leaf spot include enzyme-linked immunosorbent assay (ELISA), PCR, qPCR, and nested PCR. In recent years, Stöger & Ruppitsch (2004) developed a highly sensitive PCR kit called REDExtract-N-Ampk Plant PCR-Kit, which enhances PCR sensitivity by improving nucleic acid extraction efficiency, enabling the detection of *X. fragariae* on asymptomatic plants. Following this, real-time PCR was developed (Cubero *et al*. 2009), increasing sensitivity by approximately 100 times. Notably, Turechek *et al*. (2008) focused on detecting the strawberry crown, and LAMP further enhanced sensitivity and made it easier for farmers to use (Wang & Turechek 2016; Gétaz *et al*. 2017). Our research team is actively collaborating with academic research institutions to develop a detection method for angular leaf spot in Taiwan.

Currently, the disease diagnosis methods for strawberry runner plants include PCR testing for anthracnose rot and selective media for Fusarium wilt. Tissue-cultured mother plants are 100% tested, while tissue culture plantlets are randomly tested at a rate of 1/100, and acclimatized tissue-cultured plants are tested at a rate of 1/1000 when necessary. The verified tissue-cultured acclimatized plants, when introduced into the facility for propagation, result in a replanting rate of less than 1% after transplanting. In recent years, farmers have gradually adopted the concept of using healthy runner plants, leading to a growing demand for healthy strawberry runner plants. Some nurseries and biotechnology companies have also started to invest in this industry. However, after the acclimatized tissue-cultured plants are moved to the field, most farmers still propagate in open-field environments, and their management practices often lead to issues such as fertilizer burn and pesticide damage, making strawberry plants more susceptible to opportunistic pathogens such as *Fusarium* sp. from the environment, causing wilting. Therefore, future efforts will still need to focus on improving cultivation environments and management practices through education, training, and on-site guidance for farmers involved in propagation.

Disease-resistant breeding

Disease-resistant breeding is one of the fundamental methods for crop disease control and an essential strategy for implementing IPM. Taking strawberry leaf blight as an example, the 'Xiang-Shui' cultivar is highly susceptible, while 'Taoyuan No. 1' is disease-resistant. When formulating IPM strategies, it is necessary to consider the disease tolerance of different cultivar. Strawberry disease resistance breeding and research related to resistance genes have made significant breakthroughs with advancements in molecular genetics and genomics. For strawberry anthracnose rot, three resistance loci, namely *RCa2*, *FaRCg1*, and *FaRCa1*, have been identified (Anciro *et al*. 2018; Salinas *et al*. 2019). However, these loci were identified based on analyses using the foreign major pathogenic species *C. acutatum* and *C. gloeosporioides*, which differ from the main pathogenic species in Taiwan, *C. siamense* and *C. fructicola*. The trials showed that it was not applicable for predicting resistance or susceptibility to *C. siamense* and *C. fructicola*. This is presumably due to the species-specific nature of disease resistance genes (Miller-Butler *et al*. 2019). Therefore, further research is needed to identify detection genes for resistance to the major pathogens causing anthracnose rot in strawberry in Taiwan. Another important case is strawberry Fusarium wilt resistance breeding. In response to the impact of Fusarium wilt on the strawberry industry in California, the University of California conducted phenotypic screening and genotypic identification of resistance in local and international strawberry germplasms. By combining various molecular genetic tools, they discovered five Fusarium wilt resistance genes, *Fw1* to *Fw5*, and used molecular markers to assist in selecting and breeding multiple new Fusarium wilt-resistant cultivars suitable for different cultivation systems (Pincot *et al*. 2022).

In 2019, the RosBREED research project, funded by the United States Department of Agriculture and the Florida Strawberry Research and Education Foundation, released the strawberry DNA testing handbook (Oh *et al*. 2019). This handbook consolidates research information on DNA molecular markers for several important strawberry traits, including resistance genes for three major diseases: crown rot (*Phytophthora cactorum*), angular leaf spot (*X. fragariae*), and anthracnose rot (*C. acutatum*), along with their molecular marker sequences, testing conditions, result interpretation, and reference cultivars. We used these molecular markers to genotype the strawberry germplasm stored at our facility. Preliminary results indicated that the anthracnose rot resistance gene molecular marker *RCa2* was ineffective in screening for resistance against the major strains of the pathogen in Taiwan. Additionally, attempts to design T-ARMS PCR molecular markers to detect resistance genes *FaRXf1* for angular leaf spot and *FaRCg1* for anthracnose rot also did not yield precise and directly applicable results, so further testing is needed (Yeh & Wei 2024).

In Taiwan, phenotypic evaluation of strawberry disease resistance was conducted by Wu *et al*. (2022), who screened 55 domestically preserved strawberry germplasms for anthracnose rot resistance by inoculating them with the representative local isolates *C. siamense* ML133 and *C. fructicola* ML356. Five cultivars (lines) exhibited significantly lower disease severity compared to the susceptible control cultivar 'Taoyuan No.1.' Among them, 'Fukuba', 'Tufts', and 'Solana' showed significantly lower conidial germination rates and appressorium formation rates on leaf surfaces compared to 'Taoyuan No.1'. Additionally, no accumulation of hydrogen peroxide was observed in infected leaf tissues, indicating that the resistance carried by these three cultivars effectively delayed the infection of *C. siamense* and *C. fructicola* (Wu 2020). The preserved line 'TYS16109' at Taoyuan District Agricultural Research and Extension Station exhibited a disease incidence area of less than 10% in both pathogen inoculation tests, showing a significant difference from 'Taoyuan No.1' and demonstrating good resistance in both leaves and crowns, making it a promising candidate as a parent in future disease-resistant breeding programs. The emerging leaf blight of strawberry

in Taiwan is caused by *Neopestalotiopsis rosae*, and the currently dominant cultivar 'Xiang-Shui' lacks resistance to this pathogen. Through detached leaf inoculation assays of 44 preserved strawberry germplasms at our institute, 24 cultivars (lines) were identified as resistant to leaf blight (Fig. 1). Selection of resistant germplasms with superior horticultural traits from this pool is planned for use as breeding parents to improve disease resistance.

Soil disinfestation and rationalized fertilization

Healthy strawberry runner plants should be cultivated in healthy soil to produce high-quality strawberry. Crop rotation, soil disinfestation, and rational fertilization are essential components of strawberry IPM. Soilborne diseases such as Fusarium wilt could persist in the soil for several years, and if soil disinfestation is not implemented in affected fields, recurring outbreaks may occur and intensify over time. Additionally, rational fertilization not only supports normal plant growth but also prevents excessive nitrogen application, which might lead to increased pest and disease severity.

1. Soil disinfestation

The use of steam for controlling soilborne diseases can be traced back to the late 17th century. Soil steam disinfestation effectively suppresses soil pathogens and weeds while enhancing the vigor of crops grown on steamed soil (Fennimore & Goodhue 2016). Due to the low cost and high efficacy of fumigants such as methyl bromide (MB), steam disinfestation was mostly replaced in horticultural crops during the 1960s (Wilhelm 1966). This chemical method eliminates both beneficial and harmful microorganisms in the soil (Ristaino & Thomas 1997; López-Aranda *et al*. 2016; Holmes *et al*. 2020). However, it not only disrupts the physical and chemical structure of the soil but also poses risks to human health and the environment, leading to increasing restrictions and even bans on their use. Consequently, alternative methods that are relatively more environmentally friendly, such as steam applicators, have been developed (Fennimore & Goodhue 2016). In recent years, anaerobic soil disinfestation (ASD) has been introduced in California strawberry fields as an alternative method (Shennan *et al*. 2014). This approach involves adding organic matter to the soil and creating an anaerobic environment by sealing off oxygen, causing microbial proliferation and oxygen depletion, ultimately leading to the extinction of soilborne pathogens under anaerobic stress. Additionally, Japan has adopted the solarization-calcium cyanamide method for soil disinfestation (Kodama & Fukui 1979), primarily applied in greenhouses. During the high-temperature summer period, organic matter and calcium cyanamide are incorporated into the soil, which is then thoroughly moistened and covered with transparent plastic film. The disinfestation effect is achieved through heat accumulation from solar energy and the release of cyanamide during the decomposition of calcium cyanamide.

Currently, soil disinfestation methods for strawberry cultivation in Taiwan vary depending on the cultivation system. In elevated cultivation facilities, most growers cover the cultivation beds with plastic film during the summer to utilize solar heating for sterilization, while a few farms install heating systems for hot water disinfection. In open field soil-based systems, most farmers do not conduct soil disinfestation after the strawberry season but instead rotate to summer crops, while a small number practice fallowing with field flooding or apply calcium cyanamide during soil preparation (Chung & Wu 2017). In response to the widespread occurrence of Fusarium wilt in open field strawberry farms in recent years, our research team provided technical guidance to farmers who had not fallowed their fields for many years, implementing either anaerobic soil disinfestation or the solarization-calcium cyanamide method based on environmental conditions in 2023 and 2024. Significant improvements were observed in most field; however, some fields did not show notable effects. Apart from the potential

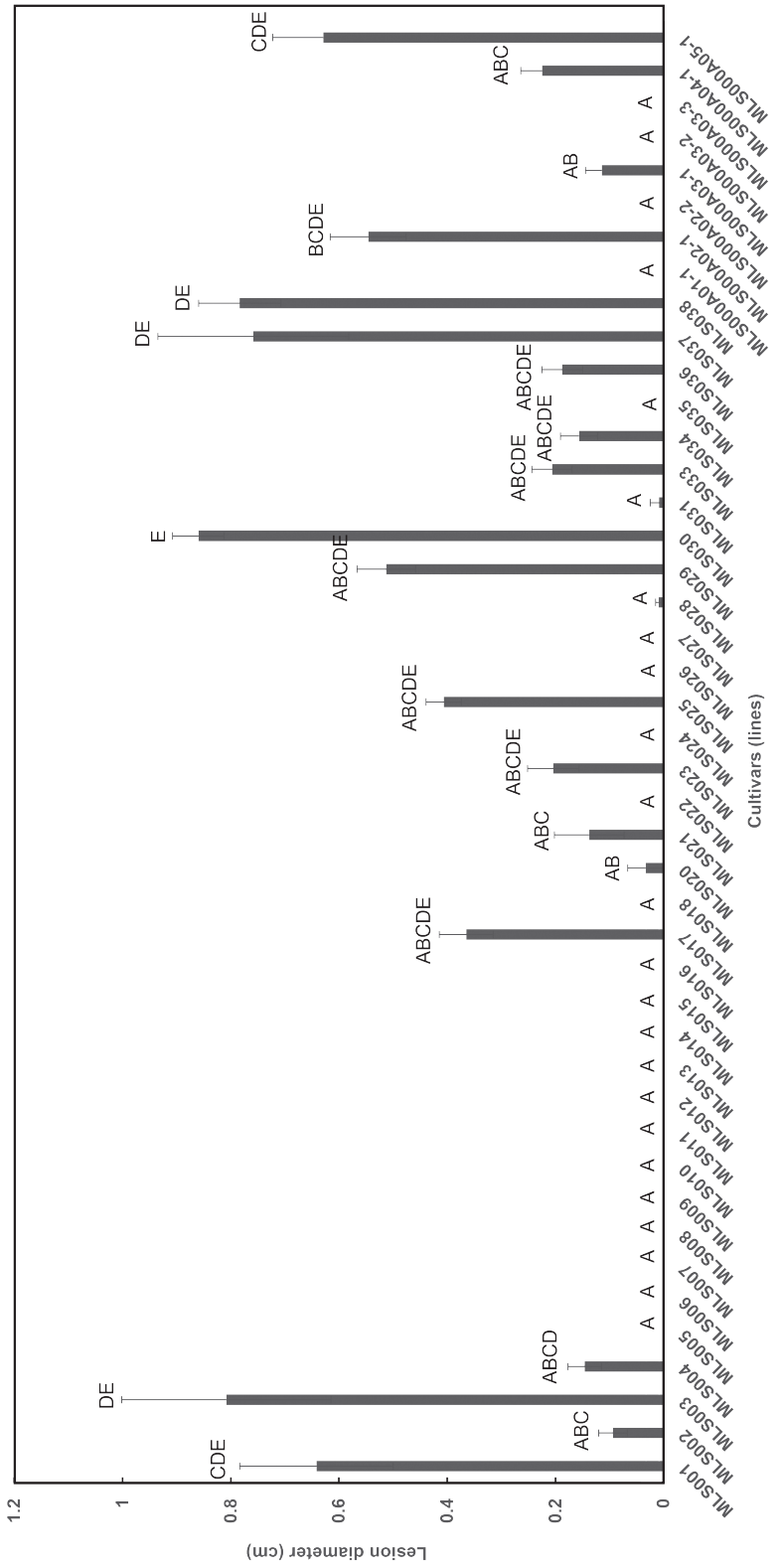


Fig. 1. Diameters of lesions on detached leaves of strawberry cultivars (lines) inoculated with *Neopestalotiopsis rosae* ML2147 at 7 d post inoculation. All bars are mean ± SEM. Different letters indicate statistically significant differences (Tukey-Kramer post hoc test, P value ≤ 0.05).

presence of infected planting materials, possible contributing factors include insufficient increases in soil temperature, inadequate soil moisture levels, and the potential for the pathogen to utilize organic matter added during anaerobic treatment (Yonemoto *et al*. 2006; Henry *et al*. 2020). These factors should be considered for future technical guidance and optimization of soil disinfestation strategies.

2. Rationalized fertilization

Strawberry farmers commonly apply large amounts of chicken waste compost, soybean fertilizer, or chemical fertilizers 4 wk before transplanting, with nitrogen application rates ranging from approximately 322 to 459 kg ha^{-1} (Table 1). To facilitate the evaluation of the impact of such fertilization rates, the nitrogen decision support system (Fink & Scharpf 1993) could be used to estimate the mineral nitrogen content of each independent component using a dynamic model (Table 2). In this system, N_0 represents the potentially mineralizable nitrogen, and k is the mineralization rate constant, which ranges from approximately 0.03 to 0.054 wk^{-1} at room temperature (Smith & Stanford 1971; Tsai 1993; Chuang *et al*. 1995). Under field conditions, the k value is not constant but rather a function of soil temperature and soil moisture (Mary & Recous 1994). The temperature relationship is expressed as $k_2 = k_1 \times Q_{10}$ $((T_2-T_1)/10)$, where Q_{10} is 4.0 (Sierra 2002). Regarding soil moisture, if rainfall before transplanting is insufficient, mineralization rate is limited by soil moisture deficit, and k is considered to be 0. After transplanting, irrigation stabilizes soil moisture, maintaining a constant k value. Based on the nitrogen application rate of 459 kg ha^{-1} commonly used by strawberry farmers (Table 1), if 50% of the nitrogen is mineralizable (Tsai *et al*. 1993), N_0 is estimated to be approximately 230 kg ha^{-1}, with an additional 60 kg N ha^{-1} from chemical fertilizers. Assuming the initial mineral nitrogen content in the soil before fertilization is 90 kg ha^{-1}, the changes in soil mineral nitrogen content following fertilization are illustrated in Fig. 2. Between the 4^{th} and 8^{th} wk after transplanting, soil mineral nitrogen (N residue) reaches its peak. According to the analysis of soil properties in severely affected strawberry fields in the Dahu region in 2023, when soil mineral nitrogen exceeds 135 kg ha^{-1}, soil electrical conductivity (EC) rises above the optimal threshold for strawberry (0.20 dS m^{-1}) (Fig. 3), making this period the most susceptible to growth disorders. After the 8^{th} wk post transplanting, soil mineral

Table 1. Investigation results of soil properties and basal fertilizer application before strawberry transplanting in Dahu Township.

Soil properties	Mountain area (n = 34)[z]	Riverside (n = 69)[z]
pH	6.00 ± 0.89	6.22 ± 0.69
EC, dS m^{-1}	0.14 ± 0.07	0.14 ± 0.10
OM, g kg^{-1}	26.7 ± 8.51	21.5 ± 4.96
Av. N, mg kg^{-1}	15.7 ± 3.24	17.6 ± 5.42
CEC, cmol+ kg^{-1}	12.2 ± 3.54	8.8 ± 2.4
N application, kg ha^{-1}	459 ± 208	322 ± 132

[z] Data are mean ± standard deviation.

Table 2. Components related to soil mineral nitrogen content.

Components	Descriptions	Dynamic model
N plant	N uptake in plant	$N_{yield} \div (1 + A \times e^{-Bt})$
N loss	N loss by leaching, runoff or denitrification	$N_s \times C \times (1 - e^{-kt})$
N humus	N from mineralization of humus and crop residues	$N_H \times (1 - e^{-kt})$
N manure	N from mineralization of oganic fertilizer	$N_0 \times (1 - e^{-kt})$
N chemical	N from chemical fertilizer	
N soil	Mineral N at begin of cultivation	
N residue	N soil + N chemical + N manure + N humus- N loss- N plant	

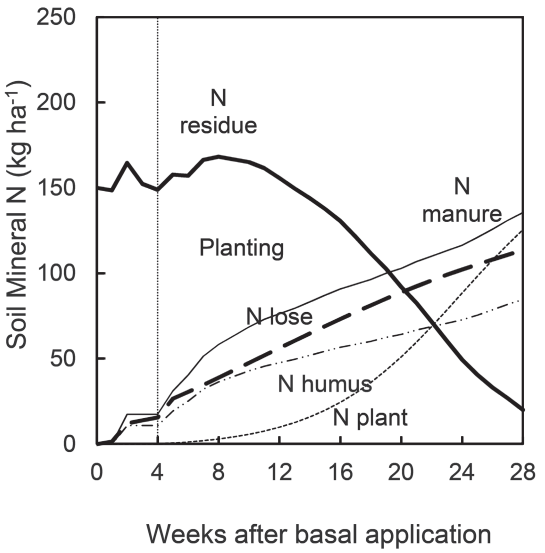


Fig. 2. Diagram of changes in soil mineral nitrogen content after base fertilizer application.

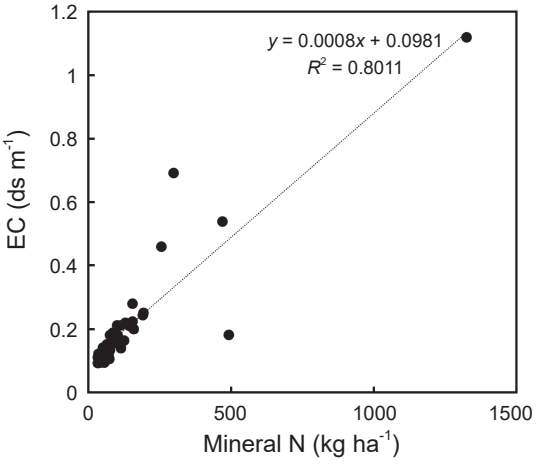


Fig. 3. Relationship between soil mineral nitrogen and soil electrical conductivity (EC) in severely diseased strawberry fields in Dahu Township, 2023.

nitrogen gradually decreases, aligning with the timing of topdressing applications by farmers.

Using meteorological data on soil temperature (at a 10 cm depth) and rainfall collected during the strawberry cultivation period in the Dahu region from 2022 to 2024, the changes in soil mineral nitrogen content under different transplanting dates and fertilization rates were further evaluated, as shown in Fig. 4. Higher N0 values resulted in greater soil mineral nitrogen levels exceeding 135 kg ha^{-1} during the early transplanting stage, with annual variations, showing the lowest levels in 2024. Fields transplanted in late September exhibited a higher degree of soil mineral nitrogen excess compared to those transplanted in late October. To mitigate early transplanting risks in strawberry production, adopting a varying fertilizer practice is recommended (FASS 1995). As shown in Fig. 4, lower N0 values combined with liquid fertilizer fertirrigation resulted in a lower risk of excessive soil mineral nitrogen accumulation. Therefore, soil analysis before basal fertilization is recommended to determine a reasonable nitrogen application rate, followed by fertigation with liquid fertilizers from transplant establishment until the end of production to maintain soil mineral nitrogen within an optimal range.

Cultivation management techniques in response to climate change

In recent years, strawberry cultivation has faced various threats and challenges due to climate change. High temperatures during the propagation stage of the runner plants have caused heat stress and inhibited growth. Additionally, intermittent heavy rains have facilitated the spread of diseases. During the fruiting period, early-stage high temperatures combined with excessive fertilization result in poor root development, increasing the incidence of soilborne diseases and disrupting the continuity of strawberry flowering. In addition to preventive measures such as facility-based runner plant propagation, delaying transplanting in soil-based areas, and rationalized fertilization, the following section will describe the cultivation management techniques currently being developed by our research team. Through the implementation of IPM strategies, we aim to address the challenges posed by climate change, reduce the spread of diseases during the runner plants stage to ensure the propagation of high-quality nurseries, and maintain consistent flowering for stable production of high-quality strawberry fruit during the fruiting period.

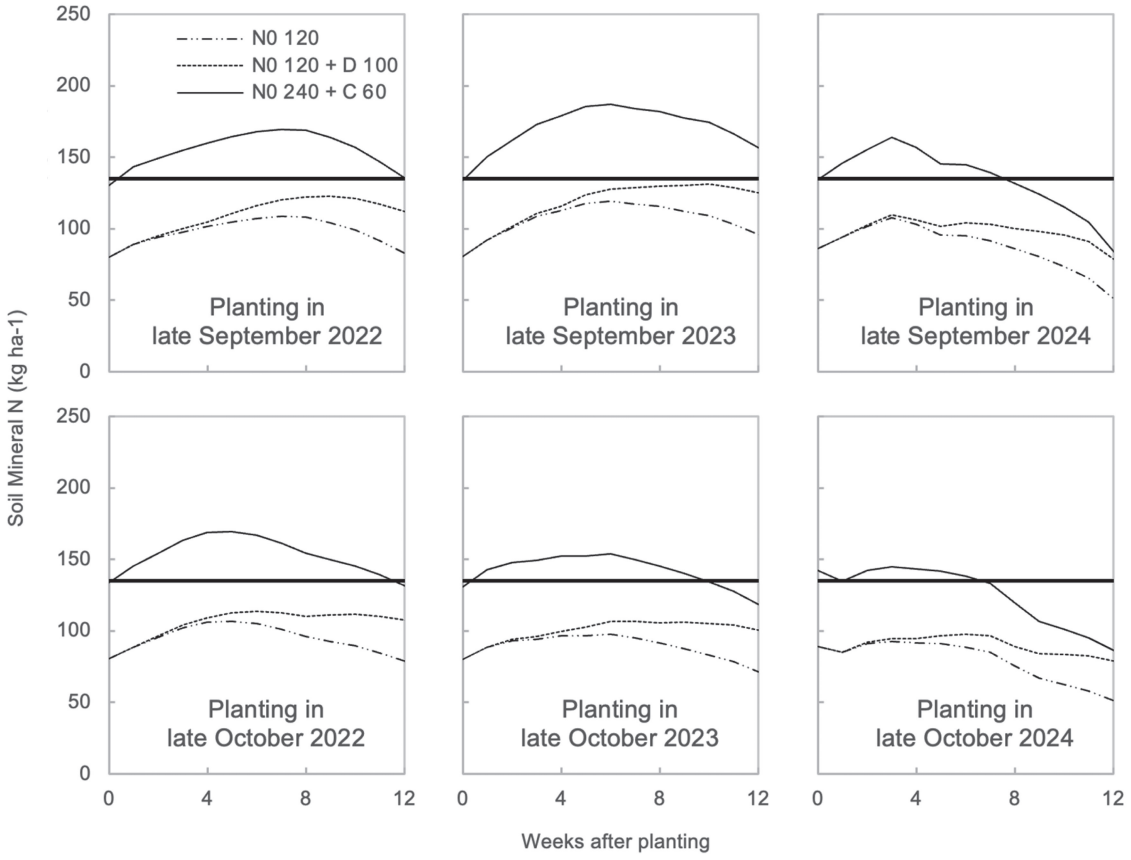


Fig. 4. The changes in soil mineral nitrogen content after transplanting during different strawberry planting periods and fertilization rates from 2022 to 2024 in Dahu Township. Data were estimated based on 10 cm-depth soil temperature and rainfall data. The horizontal line represents the soil mineral nitrogen threshold (135 kg ha^{-1}). N0 120: Organic fertilizer with 120 kg N ha^{-1}; N0 120 + D100: Organic fertilizer with 120 kg N ha^{-1} combined with liquid fertilizer applied at 100 kg N ha^{-1}; N0 240 + C60: Organic fertilizer with 240 kg N ha^{-1} combined with chemical fertilizer at 60 kg N ha^{-1}.

1. Strategies against adverse conditions during the runner plant propagation period

Strawberry runner plants are propagated using paper pots in Shizuoka Prefecture, Japan. The temperature inside the paper pots is lower, and inflorescence initiation occurs about 7 d faster. The blooming time of the terminal flowers and the harvest time of the fruit are approximately 2 wk earlier than when propagated in plastic pots. Additionally, using paper pots and plastic pots with the tray water supply method for runner plant propagation effectively prevents the spread of anthracnose rot, compared to conventional overhead irrigation (Ikari 2010). Lower root temperature (12℃) promotes vegetative growth in strawberry, increasing petiole length, leaf area, and fresh leaf weight. In contrast, higher root temperature (24℃) suppresses vegetative growth (Lieten 1997).

During the runner plant propagation period, our research team evaluated four types of nursery containers: black plastic pot, transparent plastic pot, pulp cup, and plastic plug. Soil thermometers were used to record the temperature inside the containers at 9:00, 12:00, and 15:00 from July to August. The results showed that at all three time points, the

temperature inside the pulp cup was the lowest among the four containers, while the plastic plug had the highest temperature. There was no significant difference in temperature between the two plastic pots at any time point, indicating that the color of plastic pots might have minimal influence on the medium temperature. Regarding the growth of the runner plants, black plastic pot and pulp cup performed better in above-ground growth, with the black plastic pot having significantly higher fresh and dry shoot weights than the other three containers. Root morphology varied among containers: black plastic pot exhibited obvious root circling, transparent plastic pot showed minimal root circling with some scattered thick roots, pulp cup had no root circling, and plastic plug allowed natural air pruning at the bottom, with roots adhering to the tube walls. However, root biomass showed no significant difference among different treatments. After transplanting, there was no significant difference in the time to first flowering among runner plants from four containers, but black plastic pot resulted in the highest yield. Among the four nursery containers, pulp cup maintained the lowest temperature under high summer temperatures, while black plastic pot showed the best runner plant growth and post-transplant yield (unpublished data).

2. Strategies against adverse conditions during the fruit production stage

Most major strawberry-producing countries select appropriate cultivars based on climate conditions and cultivation methods while adjusting the production period in response to climate change. In some temperate European countries and Japan, greenhouse cultivation has been developed to mitigate temperature stress. For example, only a minimal amount of open-field strawberry cultivation remained in Japan after 1995, and the area dedicated to soilless elevated substrate cultivation has continued to expand since 2000 (Yoshida 2013).

For greenhouse cultivation under high-temperature stress, in addition to comprehensive environmental temperature control, localized cooling techniques have been developed. For example, partial temperature control, such as placing plastic tubes with running cooling water next to the crown tissue, could effectively lower temperature and promote flowering (Hidaka *et al*. 2017). Additionally, ensure ventilation underneath the culture system to cool down the culture medium by the latent heat of water evaporation (Ikeda *et al*. 2007). For large scale open-field cultivation, using different mulching materials to reduce heat stress. In California, an aluminum-coated treatment was applied to the center of black plastic mulch to increase reflectivity and reduce high temperatures during the early transplanting period, while the sides remained black to retain heat during winter. Compared to the control, this treatment reduced root zone temperature by up to 3.1℃ and increased yield (Deschamps & Agehara 2019).

The primary method for mitigating high temperature stress of strawberry cultivation remains soilless elevated substrate cultivation in Taiwan. For soil-based cultivation, our research team is currently conducting trials to evaluate alternative mulching materials as substitutes for the conventional silver-black plastic mulch to alleviate excessive heat accumulation on the surface of the raised bed. Preliminary experiments have shown that certain alternative materials can reduce surface temperature by up to 4℃ compared to the control during peak noon temperatures (unpublished data). Further multi-year trials and cost benefit analyses are required to assess the feasibility of widespread adoption.

Strategies for controlling small pests

Strawberry suffers from two types of thrips. One is the leaf thrips, primarily the yellow tea thrips (*Scirtothrips dorsalis* Hood) or the southern yellow thrips (*Thrips palmi* Karny), which usually hide at the base of the petiole. They feed on the leaves through rasping, causing the leaf veins to turn dark brown. Preventive

or control measures should be implemented before transplanting to avoid the introduction of pests into the planting field along with the runner plants. The other type is the flower thrips (*Frankliniella intonsa* Trybom), which rasps the flowers with its feeding mouthparts. If the flowers are affected, they cause fruit deformities, hardening, and rust-colored discoloration, rendering the fruits unmarketable. Two-spotted spider mite (*Tetranychus urticae* Koch), commonly known as the red spider mite, is another small pest of strawberry. The damaged leaves develop tiny yellow spots, which then turn reddish-brown and spread across the entire leaf, leading to leaf wilting and drop.

Thrips and spider mites are adept at hiding and could rapidly proliferate during high-temperature periods, causing farmers to miss the optimal timing for pest control. Additionally, control agents often fail to make direct contact with the pests, leading to poor efficacy, while frequent applications of chemical pesticides contribute to resistance development (Price *et al*. 2002; Van Leeuwen *et al*. 2010; Bernardi *et al*. 2013; Lahiri *et al*. 2022). Therefore, it is necessary to implement IPM strategies, such as using colored sticky cards for monitoring or reducing pest density, applying environmentally friendly materials, and natural enemies for pest control. A Dutch biocontrol company (Koppert) has developed specialized packaging, including sachets and hang sachets containing predatory mites *Amblyseius swirskii* and *Neoseiulus cucumeris*, to target thrips larvae (Arthurs *et al*. 2009; https://www.koppert.com). The company has also developed predatory bugs of *Orius* spp. to control adult thrips (Zuma *et al*. 2023; https://www.biobest.com) and beneficial nematodes *Steinernema feltiae* to combat thrips pupae that burrow into the soil (Renkema *et al*. 2018). A Belgian biocontrol company (Biobest Shouguang Biological Control Ltd.) has also employed predatory mites for strawberry spider mite management. They recommend using sachets containing *N. californicus* at the early stages of strawberry cultivation as a preventive measure, applying 1–2 sachets per square meter at entry points where spider mites are likely to invade. *N. californicus* is a generalist predatory mite that, when used with sachets containing supplemental food, could survive even in low spider mite populations, providing long-term pest control (Fraulo & Liburd 2007). *Phytoseiulus persimilis*, on the other hand, is a more specialized predatory mite that is used as a curative treatment when spider mite populations begin to increase significantly in the field (Zhao *et al*. 2023; https://www.biobest.com).

In Taiwan, *N. longispinosus* is recommended for controlling strawberry two-spotted spider mites. During the early stages of transplanting, it is evenly released at a density of 5,000–10,000 individuals per 0.1 ha every 2 wk, and after three consecutive applications, the incidence of spider mites can be reduced while also decreasing the use of chemical pesticides (Shih 2010; unpublished data). The non-exclusive licensing of the production and release technology for this predatory mite has already been announced. Once commercialized, its release following the IPM strategy will help address the frequent pesticide application in strawberry fields, which often fails to achieve effective spider mite control. For managing flower thrips in strawberry, *Orius strigicollis* is used as a biological control agent. When thrips infestation is observed during the flowering period, natural enemies are released at a density of 5,000–20,000 individuals per 0.1 ha, effectively reducing thrips damage to strawberry fruits (Lin *et al*. 2017). Additionally, if strawberry is affected by broad mites, *N. barkeri* has been developed domestically as a biocontrol agent. In severely infested plants, a density of 50–100 individuals per m^2 is applied weekly, which has been shown to restore normal plant growth (https://goodfarms.neophoen.com).

In addition, to reduce the usage of chemical pesticides, Agricultural Chemicals Research Institute (ACRI, MOA) has developed a rubber-cap-type thrips alarm pheromone. Farmers could begin hanging these pheromone dispensers at the early stages of strawberry cultivation before

thrips populations are established. The rubber cap should be placed upside down approximately 1 meter above the strawberry plants, allowing the pheromone to diffuse downward and outward through air circulation, causing thrips to become restless, thereby reducing their residency and oviposition rates, ultimately achieving a control effect. The recommended hanging density is one pheromone dispenser every 2 m, with approximately 300 units per 0.1 ha, and each dispenser remains effective in the field for about 6 mo. During the implementation of IPM programs for strawberry, the thrips alarm pheromone has been successfully promoted. In addition to its small size, ease of installation, and long-lasting effect, the key to its success lies in effectively reducing thrips population density, improving fruit quality, and lowering costs associated with purchasing and using pesticides. However, this pheromone is still in the trial promotion stage in Taiwan and has not yet been registered as a pesticide, requiring further efforts from governmental agencies for official approval.

Although control agents such as natural enemies and pheromones are more costly compared to chemical pesticides, when integrated with IPM strategies like population density monitoring and early prevention, they ultimately offer greater advantages in terms of production costs, economic benefits, and environmental sustainability over the frequent application of chemical pesticides.

AI and decision support tools in IPM

1. Image recognition and early warning system for diseases and pests in strawberry

In recent years, due to global climate change, modern technology is needed to assist farmers to manage increasingly severe outbreaks of diseases and pests. The University of Florida has developed a strawberry disease early warning system (Strawberry Advisory System; SAS) (Montone *et al*. 2016; Kondaparthi *et al*. 2024). The system automatically collects temperature through weather monitoring stations and combined with leaf wetness duration (LWD) data, which is estimated using mathematical models. These combined data are then used in formulas to calculate the infection index (INF). Based on the INF values, the risk is classified into three levels- low, medium, and high- and color-coded accordingly. This system provides recommendations on whether farmers should apply fungicides. Research results indicate that by using the information of the early warning system and applying control materials when necessary, fungicide application can be reduced by about 50%, with no negative impact on disease control and yield. To facilitate use by farmers, SAS also developed a mobile app version, simplifying the interface and offering disease risk levels and forecasts. It provides fungicide application suggestions through a simple questionnaire to reduce the risk of resistance development. In Lithuania, a European country, field weather monitoring data have been used to develop a system to predict the occurrence period of gray mold. The system, iMETOS® (Rasiukevičiūtė *et al*. 2019), is based on disease early warning and fungicide application patterns. In experimental fields using the system, the yield was higher than in the control area (which received no treatment), and the proportion of fruit rot was lower. Compared to conventional fungicide application areas, no differences were observed in yield or fruit rot proportions. South Korea, one of Asia's major strawberry-producing countries, has established a data integration and analysis platform (Farm as a Service, FaaS) (Kim *et al*. 2018) using field environmental big data. This platform predicts the occurrence of strawberry gray mold based on field temperature and humidity conditions, offering better pest management strategies within smart farming, in addition to cultivation management practices such as fertilization and irrigation.

Our research team, in collaboration with the Department of Plant Pathology and Microbiology, the Department of Agronomy, and the Department of Biomechatronics Engineering at National Taiwan University, has developed

a "Strawberry Pest and Disease Recognition Robot and Disease Early Warning System". For disease early warning, five experimental fields were established in major strawberry production areas, equipped with a weather station to collect climate data. Disease severity was assessed through regular field surveys. Using logistic regression combined with field survey data on strawberry disease severity and microclimate data, two disease prediction models have been established. By analyzing the past 7 d daily high temperatures and low humidity data, these models can predict the likelihood of anthracnose rot and leaf blight worsening within the next 7 d, allowing farmers to monitor disease development and implement timely control measures. For anthracnose rot, the model exhibited an AUC of 0.918 and an accuracy of 0.811; for leaf blight, the model's AUC was 0.951 with an accuracy of 0.839 (unpublished data). However, compared to the cultivation models with other countries, strawberry farms typically have smaller individual cultivation areas in Taiwan, and the accuracy of disease warning systems is significantly influenced by factors such as topography, microclimate, and cultivation management practices. For the successful implementation of precise applications in the future, it is necessary to accumulate years of survey data and validation. For image recognition, SqueezeNet was adopted as the model architecture, applying deep learning and utilizing over ten thousand field images of pests and diseases to train and test the recognition model. After training, the model can identify five types of strawberry pests and diseases-anthracnose rot, leaf blight, angular leaf spot, damage of spider mite and lepidopteran larval-with an overall accuracy rate of 98.3% (Chiu *et al*. 2022). This system will help farmers distinguish between visually similar symptoms on strawberry leaves. By integrating the image recognition system, disease early warning system, and control recommendations into a user-friendly LINE bot interface, farmers will be able to access relevant information through commonly used messaging apps (Fig. 5). This approach enables fast and accurate pest and disease identification, promotes better pesticide use practices, reduces chemical pesticide application, and enhances strawberry quality in the future.

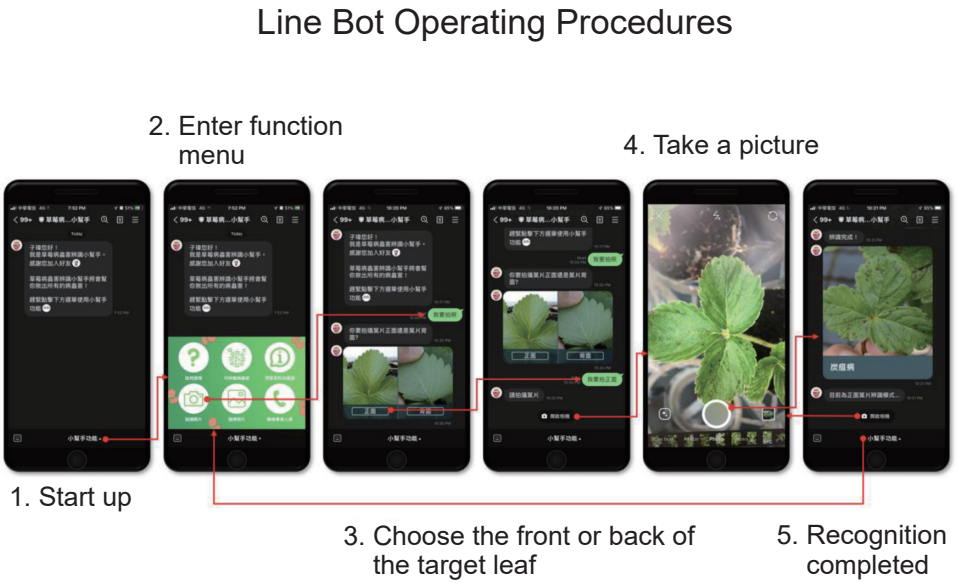


Fig. 5. The Line bot could assist farmers in quickly identifying major strawberry pests and diseases in the future.

Case studies and field implementation in Taiwan

1. Case study on the implementation of IPM technology in severely Fusarium wilt infested soil-based fields in 2023 to 2024

Case I: This case involves a strawberry farmer in Dahu Township, Miaoli County, whose field suffered severe plant loss and wilting at the end of 2022, with a loss rate of 100%. On-site investigation confirmed that the issue was caused by Fusarium wilt infected runner plants. Therefore, starting in June 2023, our research team provided assistance in monitoring pests and diseases during the runner plants period, guiding the farmer in identifying pest and disease types, implementing thorough field sanitation, and determining critical periods for control. During cultivation period in 2023, soil analysis was conducted before and after land preparation to assess soil fertility. Based on the analysis results, appropriate amounts of organic compost were recommended as base fertilizer to prevent excessive EC. After transplanting, different liquid fertilizers were supplied according to the various growth stages of strawberry along with the application of beneficial microorganisms, including *Bacillus* spp. and *Trichoderma* spp.. As a result, the replanting rate was successfully reduced to below 10%, from an economic perspective, a 0.4 ha plot incurred a loss of approximately 700,000 to 800,000 NTD in 2022, while in 2023, the net income from the same plot reached around 1,700,000 to 1,800,000 NTD, demonstrating significant effectiveness.

Case II: The assisted farm is located approximately 300 m from the tourist attraction "Dahu Winery" in Dahu Township, Miaoli County. The farmer suffered from a significant yield reduction over the past two years. After transplanting in late September to early October 2023, disease symptoms began appearing in mid-November, prompting the farmer to seek assistance from our research team. On-site investigation confirmed that Fusarium wilt was the primary cause of damage. Soil sampling and analysis indicated multiple signs of excessive fertilization. Consequently, for that growing season, the farmer was advised to apply biopesticides targeting Fusarium wilt and to cease additional fertilization to mitigate field damage. During the summer of 2024, the farmer implemented partial fallow management and, in early July, conducted soil disinfestation using the solarization-calcium cyanamide method under our guidance. Temperature loggers were buried at a soil depth of approximately 15 cm to monitor the effectiveness of disinfestation. After 52 d, the cumulative data confirmed that the soil temperature exceeded 35℃ for 652 h, with 186 h exceeding 40℃. Following soil disinfestation, base fertilizer and beneficial microorganisms including *Bacillus* spp. and *Trichoderma* spp. were applied according to our recommendations, and runner plants propagated by farmers regularly guided by our research team were transplanted in late October. A neighboring field that likewise suffered from severe Fusarium wilt in the prior period was utilized as the untreated control for comparison. The field showed an approximate 8% replanting rate (due to anthracnose rot), which was a significant improvement compared to the nearly 65% Fusarium wilt incidence observed in the adjacent untreated field. As of the end of February 2025, fruit production was at its peak. Although disinfestation increased costs, replanting costs were reduced by 86%. The demonstration area reduced fruit yield loss by 74% and achieved a 382% increase in sales revenue when compared to the control area. These results demonstrate the economic benefits of integrating IPM strategies.

Limitations, knowledge gaps, and future directions

Strawberry is a temperate crop, and its cultivation in Taiwan with a subtropical climate faces multiple pest and disease threats, further compounded by the challenges of climate change. Collaboration between research institutions and farmers is essential to effectively address industry issues with developed technologies.

Strawberry healthy runner plants propagation

system has been implemented since 1990 in Taiwan (Lee 1993), but it garnered more attention in the past decade due to the severe occurrence of diseases. The diseases not only led to a significant increase in replanting rates during the early stages of transplanting, raising input costs, but also directly affected the yield per unit area. To reduce the risk of disease spread due to latent infections from self-retained mother plants, our research team has guided farmers in using tissue culture plants that have been acclimatized in a controlled facility environment (G1). In recent years, several companies have invested in the production of G1 to provide farmers with a source of mother plants for runner plants propagation. However, quality control during the acclimatization stage in greenhouses and the management practices after transplanting to the field still require assistance through education, training, and on-site guidance to help growers and farmers improve the quality of runner plants and gradually implement professional runner plants propagation.

In recent years, climate change has posed significant challenges to strawberry production, particularly during summer, with high temperature, heavy rainfall, and multiple rainfall events within a single day, as well as high temperature during the early transplanting stage. These are unavoidable issues for the strawberry industry. To mitigate the risk of pest and disease outbreaks triggered by environmental stress and to stabilize fresh fruit yield, it is essential to adopt adaptive cultivation management techniques, invest in protective facilities, and implement localized cooling methods for plants (Morton *et al*. 2017; Menzel 2023, 2024).

Strawberry production in Taiwan has long been dominated by large-scale monoculture of a single cultivar. However, as a high-value crop with significant agritourism benefits, strawberry cultivation can attract consumer traffic during the production season, stimulating the surrounding tourism industry. Therefore, diversifying cultivars is recommended to extend the strawberry season by utilizing differences in flowering and fruiting times among cultivars while also reducing the risk of pest and disease outbreaks associated with monoculture. For instance, 'Taoyuan No. 1', the dominant cultivar since its promotion in 1990, has been cultivated for nearly 35 years and is highly susceptible to anthracnose rot and powdery mildew. Since 2019, the rapid expansion of 'Xiang-Shui', which now accounts for approximately 80% of the cultivation area, has resulted in the emergence of leaf blight as the primary disease. Compared to 'Taoyuan No. 1', 'Xiang-Shui' exhibits higher resistance to anthracnose rot and powdery mildew. The most environmentally friendly and labor-saving approach to managing disease issues is the cultivation of disease-resistant cultivars. However, strawberry breeding in Taiwan still relies primarily on traditional hybridization, with breeding goals focused on economic yield and desirable horticultural traits as the main selection criteria. Disease resistance is primarily assessed through field observations, but the lack of effective early screening, coupled with the influence of climate and cultivation conditions on disease resistance performance, may lead to reduced resistance in newly released cultivars. This could impact the willingness of farmers to propagate and cultivate new cultivars.

In recent years, in addition to continuous efforts by research institutions, farmers and nurseries have also been actively selecting and breeding new strawberry cultivars. If more breeding-related resources can be allocated, future strawberry cultivars intended for commercial cultivation could be evaluated for resistance or susceptibility to major diseases through the screening platform gradually established by our research team. This would ensure that, in addition to cultivation characteristics, fundamental data on disease resistance or susceptibility are available during the promotion of new cultivars, facilitating the development of comprehensive IPM strategies and proactive disease management. In the future, integrating marker-assisted selection with high-throughput plant phenotyping technologies is expected to reduce the need for extensive field selection while accelerating the breeding process,

aligning with the long-term goal of developing disease-resistant strawberry cultivars.

Accurate identification of pests and diseases is a prerequisite for effective strawberry IPM implementation, as proper diagnosis ensures targeted and precise pesticide application. Our research team will continue collaborating with interdisciplinary research groups to develop computer programs trained through machine learning and deep learning for recognizing strawberry pests and diseases. Additionally, by integrating expert decision support systems, we aim to provide accurate and appropriate control strategies based on different pest and disease occurrences under varying environmental conditions, crop stages, and field information. This approach will assist farmers in accurately identifying pests and diseases in real time without expert assistance, enabling successful pest management while reducing the likelihood of incorrect pesticide applications.

Differences in field environmental conditions, cultivation management practices, and strawberry cultivars lead to variations in pest and disease occurrences, resulting in different levels of economic loss. Farmers require corresponding preventive or control measures, while technologies developed by research institutions must be efficiently and rapidly disseminated. Close collaboration with locally trained plant doctors is a key factor in achieving this goal. For example, in 2024, our research team worked with regional plant doctors to promote soil disinfestation practices in soil-grown strawberry fields. Our team developed the extension strategy and implementation timeline, conducted regular meetings to discuss and monitor progress, and established communication groups to provide timely field-specific recommendations. Additionally, we led plant doctors in hands-on soil disinfestation procedures, field diagnostics, and post-transplanting assessments of plant growth to determine appropriate liquid fertilizer application frequencies and irrigation volumes. The outcomes of these efforts were showcased through four demonstration and observation events held from late 2024 to February 2025, with over 300 participants. These events not only facilitated in-depth discussions between farmers and the implementation team but also encouraged neighboring farmers to adopt similar practices.

CONCLUSION

The current strawberry yield in Taiwan is approximately 17.96 metric tons per hectare, which is about 56% of the per-unit-area yield in Japan, a well-known strawberry-producing country favored by consumers. Besides inherent climatic limitations, this yield gap can potentially be narrowed through the introduction of new cultivars as breeding materials, improvements in cultivation management techniques, and the implementation of the IPM strategies for strawberry pests and diseases developed and promoted by our research team (Fig. 6). These measures aim to mitigate the risks posed by natural disasters and pest infestations, enhance strawberry yield and quality, increase income of farmers, and meet consumer market demand while simultaneously achieving ecological benefits through environmentally friendly practices.

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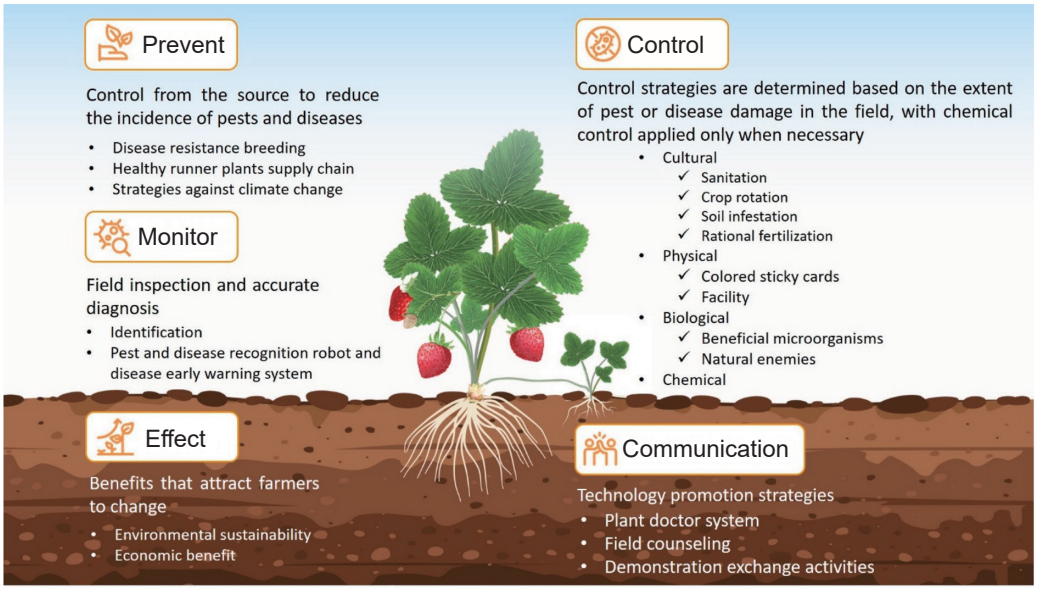


Fig. 6. Integrated pest management (IPM) strategies for strawberry cultivation.

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臺灣草莓生產之整合性病蟲害管理策略：技術創新與實施挑戰之綜述

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摘要

鐘珮哲、賴巧娟、葉人豪、蔡正賢、李怡蓓、鄭哲皓、呂秀英。2026。臺灣草莓生產之整合性病蟲害管理策略：技術創新與實施挑戰之綜述。台灣農業研究 75(1):1–26。

草莓為極具經濟價值之作物，國內栽培面積約 586 ha，主要產區位於苗栗縣 (約佔總生產面積 89.1%)，每當草莓生產期間總是吸引大批觀光客前往，帶動周邊產業發展。近十多年來草莓產業面臨病蟲害威脅、品種更迭及氣候變遷等挑戰，栽培難度逐年增加。本研究團隊以整合性病蟲害管理 (integrated pest management; IPM) 預防勝於治療的基礎，依草莓不同栽培階段與短中長期目標執行以下研發輔導策略：(1) 建立國內草莓健康種苗供應鏈，開發重要特定病害檢測技術落實於草莓種苗病害驗證作業須知，並輔導產業朝向專業育苗分工發展；(2) 建立重要病害耐 (感) 受性篩選平臺，確認國內種原對病害之耐 (感) 受性，並將結合分子標誌輔助育種與高通量植物表型分析技術，未來可望減少大量田間選拔工作並且提升育種速度；(3) 因應氣候變遷，調適育苗期與產果期栽培管理策略以降低高溫對草莓生產之影響；(4) 草莓定植前輔導農民進行土壤消毒、依土壤分析數據施用基肥及定植後合理化追施液肥；(5) 與跨領域團隊合作利用機器學習或深度學習等訓練電腦程式辨識草莓病蟲害種類，同時結合專家決策輔助系統幫助農民即時且正確地辨識病蟲害並成功防治。期望藉由 IPM 技術的推廣，逐步提升國內草莓產量與品質，不僅增加農民收益且友善環境同時滿足消費市場需求。

關鍵詞：健康種苗、抗病育種、氣候變遷、土壤消毒、深度學習。

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