

Evidence Appraisal and Engineering Translation of Ultraviolet Control for Crop Diseases: A Systematic Review

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Abstract

Ultraviolet radiation is increasingly used as a controllable physical technology for crop disease management, but inconsistencies in parameter reporting, the validation scale, and engineering evidence hinder cross-study comparisons and practical translation. Following the PRISMA 2020 statement, this systematic review searched the Web of Science Core Collection and IEEE Xplore, screened eligible studies, and conducted full-text data extraction and structured coding. A total of 80 studies were evaluated across four domains: UV treatment parameter reporting, highest validation level, translational maturity, and engineering characteristics of application equipment. The treatment frequency or number of applications and wavelength were explicitly reported in 83.8% and 76.3% of studies, respectively, whereas irradiance and post-treatment light or dark conditions were reported in only 36.3% and 35.0%. In 57.5% of studies, the highest validation level remained limited to in vitro pathogen assays, detached-material experiments, or controlled-environment whole-plant experiments; low and low-medium translational maturity together accounted for 62.5%. Among the 11 equipment-related studies included in this review, the operating speed and target-surface dose calibration were reported more frequently than within-canopy dose uniformity, shading effects, and operational control. UV-based crop disease control is progressing toward field and equipment applications, but incomplete parameter reporting, discontinuities in the production-scale evidence chain, and unstable dose delivery still constrain reproducibility and scale-up. Future research should establish minimum reporting standards, strengthen multi-site and multi-season validation, translate biologically effective doses into equipment operating parameters, and develop closed-loop control based on actual target-surface dose monitoring.

Keywords: ultraviolet radiation; crop diseases; systematic review; evidence appraisal; crop protection equipment



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1. Introduction

Crop diseases are major biotic constraints on stable agricultural production, product quality, and farm profitability. Powdery mildew [1–3], gray mold [4,5], downy mildew [6–8], and anthracnose [9], for example, can infect leaves, flowers, and fruit and spread rapidly under favorable environmental conditions. Crop disease management still relies heavily on chemical pesticides, but prolonged or inappropriate use may increase the risk of pesticide residues in agricultural products [10,11]. Within integrated crop disease management, environmentally compatible biological control has become an important route for reducing dependence on

chemical pesticides [12–14], although its efficacy is often inconsistent [15,16]. Physical approaches use forms of physical energy, including light, sound, electricity, pressure, and plasma, to suppress harmful organisms [17,18]. These approaches generally require fewer chemical inputs, offer adjustable treatment parameters, and are amenable to equipment integration. Among them, UV technology has demonstrated advantages in food processing [19–21], microbial control [22,23], and detection technologies [24,25], including the absence of chemical residues, tunable wavelengths and doses, and suitability for automated applications. With continuing advances in UV light-emitting diodes (LEDs), UV sources also provide greater design flexibility in wavelength selection, modular arrangement, and directional irradiation [26], thereby supporting the development of UV-based crop protection equipment.

UV radiation can directly damage pathogen nucleic acids [27], proteins [28], and cellular structures [29]. In plant systems, it may also induce reactive oxygen species, secondary metabolism, and the expression of pathogenesis-related genes, thereby enhancing host defense responses [30,31]. Unlike surface disinfection in foods, UV-based crop disease control involves interactions among the pathogen, host plant, environment, and application equipment. The pathogen species, infection stage, and exposure site determine whether UV radiation can reach the biological target; the crop cultivar, growth stage, and canopy architecture affect tissue tolerance and the dose actually received; and post-treatment illumination may influence pathogen photoreactivation. Consequently, effective wavelengths, doses, exposure durations, and treatment frequencies obtained in one study cannot be transferred directly across crop–pathogen systems. Doses that are too low may fail to provide stable disease suppression, whereas excessive doses or overly frequent treatments may cause leaf injury, growth inhibition, or quality changes. Establishing a dose window that balances pathogen suppression with crop safety is therefore a fundamental issue for both UV disease-control research and equipment application.

In recent years, research on UV-based crop disease control has expanded from *in vitro* pathogen assays to whole-plant, greenhouse, field, and mobile-equipment applications. Nevertheless, reporting remains inconsistent for key parameters such as the wavelength, irradiance, irradiation dose, exposure duration, treatment frequency, and post-treatment light or dark conditions. Effective laboratory doses have also not been adequately translated into executable equipment parameters, including the lamp output, lamp-to-target distance, travel speed, treatment path, and repeat-application frequency. Engineering issues such as canopy shading, dose uniformity, and monitoring of the actual dose delivered to target surfaces have not been systematically evaluated. Existing reviews have primarily addressed mechanisms of UV-mediated disease suppression, efficacy against specific diseases, or individual equipment cases; a unified, structured appraisal of the parameter-reporting completeness, validation scale, translational maturity, and engineering evidence remains lacking.

Accordingly, this systematic review was conducted in accordance with the PRISMA 2020 statement to identify, screen, and extract full-text data from studies of UV-based crop disease control. The review focused on the reporting of UV treatment parameters, the highest validation level reached, the translational maturity, and, for equipment-related studies, the operating speed, target-surface dose calibration, dose uniformity, canopy shading, automatic control, and validation in application environments. The objectives were to identify major gaps in the current evidence base and to support standardized reporting and the equipment-oriented translation of UV disease-control research.

2. Materials and Methods

2.1. Data Sources and Search Strategy

This systematic review follows the PRISMA 2020 guidelines [32]. This systematic review was not registered. The completed PRISMA 2020 checklist is provided as

Supplementary File S3. Web of Science Core Collection and IEEE Xplore were used as literature sources, and all searches were completed on 25 July 2026. The Web of Science Core Collection was selected for its broad coverage of plant science, plant pathology, agriculture, and related biological research, whereas IEEE Xplore was included to identify engineering studies involving UV application equipment, robotic platforms, automation, and control systems. Searches covered the title, abstract, and author-keyword fields in Web of Science and the All Metadata field in IEEE Xplore. Results were restricted to original English-language journal articles, with no restriction on the publication year.

A main search and an equipment-specific supplementary search were conducted separately in Web of Science. The main search combined terms related to artificial UV treatment, crops or plant pathogens, and disease-control or pathogen-response outcomes. The equipment-specific search additionally included terms related to irradiation devices, mobile platforms, robotic systems, lamp arrays, and automation. IEEE Xplore was searched to identify equipment, robotic, and control-system studies that might not be adequately represented in the Web of Science results, with records restricted to Journals and Magazines. Search terms were combined using Boolean operators, truncation, and proximity operators where supported by the database. Records were exported separately, merged, and checked for duplicates. The complete search strategies and numbers of records retrieved are provided in Supplementary Table S1.

2.2. Study Screening and Eligibility Criteria

After deduplication, title and abstract screening was followed by a full-text eligibility assessment. Records clearly unrelated to UV-based crop disease control were excluded during title and abstract screening, whereas records for which eligibility could not be determined were retained for the full-text assessment. The study-identification and screening process is presented in Figure 1, and the inclusion and exclusion criteria are summarized in Table 1.

For articles containing both eligible and ineligible components, only experiments and results that met the prespecified scope were extracted. Postharvest studies were included only when they explicitly evaluated plant pathogens, disease incidence, or decay control. Studies that assessed only storage quality, shelf life, or senescence were excluded.

Table 1. Inclusion and exclusion criteria.

Criterion	Inclusion Criteria	Exclusion Criteria
Study subject	Agricultural crops, horticultural plants, disease-related model plants, and fungi, oomycetes, bacteria, or other plant pathogens capable of causing plant disease	Studies unrelated to agricultural crops, horticultural plants, or plant pathogens; studies focused exclusively on insects, mites, or weeds
UV intervention	Treatment with UV-A, UV-B, UV-C, far-UVC, or combined wavebands delivered by a controllable artificial light source	Studies in which natural solar UV radiation, climate change, altitude, or seasonal UV variation was the principal factor; studies evaluating only UV-transmitting or UV-blocking materials
Outcomes assessed	Plant disease, pathogen growth or survival, host resistance responses, disease-control efficacy, or UV equipment, dose delivery, operating control, and application validation for disease management	Studies assessing only general UV stress, plant growth, quality, or metabolic changes without reporting disease-, pathogen-, or disease-control-equipment-related outcomes

Table 1. Cont.

Criterion	Inclusion Criteria	Exclusion Criteria
Study objective	Evaluation of the effects of UV treatment on pathogens, disease development, host resistance, or the performance of disease-control equipment	Studies primarily concerned with UV mutagenesis, strain selection, or experimental evolution; studies focused solely on postharvest preservation, ripening, or senescence without disease-related outcomes
Publication type	Original English-language research article with full text sufficient for an eligibility assessment and data extraction	Reviews, conference papers or abstracts, book chapters, theses, patents, editorials, and other non-original publications

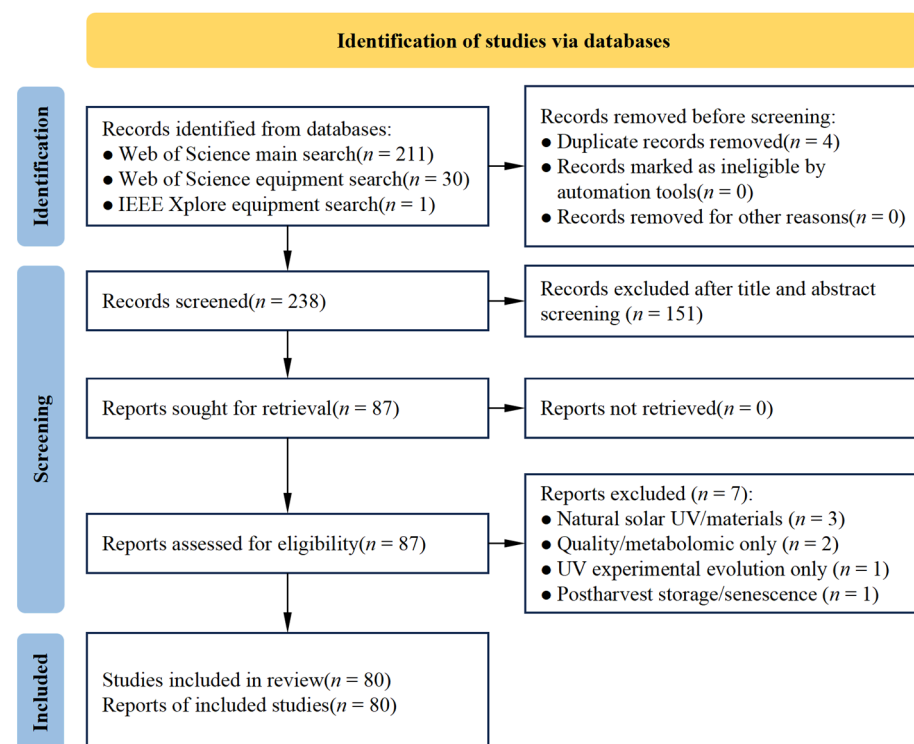


Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion.

2.3. Data Extraction and Classification Coding

Full-text data were extracted from all included studies using a prespecified extraction form. The individual article was the basic unit of analysis. When an article included multiple UV wavebands, pathogens, treatment conditions, or experimental settings, all relevant information was retained, but the article was not split into multiple independent studies.

The following information was extracted: bibliographic information, including the publication year, title, authors, journal, DOI, and country or region; study-subject information, including the plant or crop, disease, pathogen, pathogen type, UV treatment target, and study objective; UV-treatment information, including the waveband, wavelength or wavelength range, light-source type, irradiance, irradiation dose, exposure duration per treatment, treatment frequency or number of applications, treatment timing, and post-treatment light or dark conditions; experimental and outcome information, including the experimental setting, pathogen growth or survival outcomes, plant-disease outcomes, host defense responses, and crop-safety, yield, and quality outcomes. For studies involving equipment or operating platforms, additional data were extracted on the equipment type, lamp arrangement, operating speed, lamp-to-target distance, target or actual delivered

dose, target-surface dose measurement, dose uniformity, canopy shading or reflection, automatic control, and validation in greenhouse, field, or production-scale settings. These variables corresponded directly to the review objectives concerning the treatment parameters, evidence level, and engineering translation.

To ensure consistent classification across studies, selected variables were coded using standardized categories. UV wavebands were recorded as UV-A or near-UV, UV-B, UV-C, far-UVC, or combined treatments for which the waveband was unspecified or could not be separated. When a study investigated multiple distinguishable wavebands, information for each waveband was retained. Pathogens were classified as fungi, oomycetes, bacteria, mixed or unspecified, or not reported; rust fungi and other obligate biotrophic fungi were classified as fungi. Experimental settings were classified according to the highest scale actually reached: in vitro pathogen or molecular-mechanism experiments; detached tissue, seed, or seedling experiments; controlled-environment whole-plant experiments; greenhouse or protected-cultivation experiments; field experiments; and production-scale or equipment-application validation.

Both the values reported in the original articles and standardized values were retained for the irradiance and irradiation dose. Where units could be converted unambiguously, the irradiance and dose were standardized to W/m^2 and J/m^2 , respectively. Standardization was limited to dimensional and unit conversion; unreported parameters were not inferred from relationships among irradiance, the exposure duration, and the dose. Information absent from the original article, reported incompletely, or expressed with ambiguous units was coded as not reported or partially reported, as appropriate, and was not inferred from adjacent experimental conditions or typical equipment specifications.

A study was classified as an equipment study only when it explicitly addressed UV equipment design, dose delivery, operating performance, or application validation. The use of a fixed UV source as a laboratory treatment tool did not, by itself, qualify a study as equipment-related. The highest validation level, completeness of UV-parameter reporting, and translational maturity of each study were further assessed using prespecified rules, as described in Section 2.4.

2.4. Evidence Appraisal and Statistical Analysis

The included studies were appraised in 4 domains: reporting completeness of UV treatment parameters, highest validation level, translational maturity, and engineering characteristics of equipment-related studies. These indicators were used to characterize reporting, the experimental scale, and application translation and were not intended as conventional risk-of-bias or study-quality assessments.

Reporting completeness was assessed for 6 UV treatment parameters: wavelength, irradiance, irradiation dose, exposure duration per treatment, treatment frequency or number of applications, and post-treatment light or dark conditions. Each parameter was coded as clearly reported, partially reported, or not reported and assigned a score of 1, 0.5, or 0, respectively. Clearly reported indicated that directly identifiable values, units, or treatment conditions were provided. Partially reported indicated that information was available for only some treatment groups, was qualitative, or was insufficient to characterize the parameter fully. Not reported indicated that no corresponding information was identified in the full text.

The UV-parameter completeness score for each study was calculated as follows:

$$C = \frac{\sum_{i=1}^6 s_i}{6} \times 100\% \quad (1)$$

where C is the parameter-completeness score and s_i is the coded value for the i th parameter. Studies were classified as complete ($C \geq 80\%$), partially complete ($50\% \leq C < 80\%$), or incomplete ($C < 50\%$). The primary results were the numbers and proportions of studies in which each parameter was clearly reported, partially reported, or not reported; the composite completeness category was used as a supplementary indicator.

To characterize the experimental scale reached and the extent of application translation, studies were classified by the highest validation level and translational maturity. The decision criteria are presented in Table 2. Translational maturity was determined hierarchically according to the criteria presented in Table 2. When a study met the criteria for more than one level, it was assigned to the highest applicable level. Data tabulation, descriptive analyses, and figure preparation were performed using Microsoft Excel 2019 (version 2508; Microsoft Corporation, Redmond, WA, USA).

Table 2. Criteria for determining the highest validation level and translational maturity.

Evaluation Dimension	Level	Criteria
Highest validation level	In vitro pathogen or molecular mechanism	Studies limited to pathogen culture, spore or mycelial responses, survival and repair processes, or related molecular mechanisms
	Detached tissue, seed, or seedling	Validation using detached leaves or fruit, seeds, or early seedlings
	Controlled-environment whole-plant experiment	Whole-plant disease experiments conducted in growth chambers, controlled-environment rooms, or similar settings
	Greenhouse or protected-cultivation experiment	Validation conducted in greenhouses, high tunnels, or other protected-production environments
	Field experiment	Disease-control experiments conducted in open-field plots or commercial fields
	Production-scale or equipment-application validation	Development of dedicated equipment or validation of actual dose delivery, continuous operation, automatic control, or application in a production environment
Translational maturity	Low	Only in vitro pathogen, molecular-mechanism, or detached-material experiments; no whole-plant validation
	Low–medium	Seed, seedling, controlled-environment whole-plant, or equipment-prototype testing completed, but greenhouse, field, or stable-operation validation lacking
	Medium	Disease-control efficacy validated in a greenhouse or protected environment with basic treatment conditions reported, but field or systematic equipment evaluation lacking
	Medium–high	Repeated or continuous application evaluated under near-production conditions, including dose delivery, crop safety, or selected operating performance, but full field or production validation remains insufficient
	High	Disease-control efficacy validated under field or actual production conditions, with corresponding dose, treatment frequency, or operating conditions reported

3. Results

3.1. Study Selection

The searches identified 242 records. After 4 duplicates were removed, 238 records underwent title and abstract screening, of which 151 were excluded. The full texts of 87

articles were assessed for eligibility. Seven articles were excluded because they focused on natural solar UV or UV-transmitting materials ($n = 3$), quality or metabolic outcomes without disease-related outcomes ($n = 2$), UV mutagenesis or experimental evolution ($n = 1$), or postharvest storage or senescence without disease-related outcomes ($n = 1$). A total of 80 studies were included in the review (Figure 1), and their characteristics are provided in Supplementary Table S2.

3.2. Characteristics of the Included Studies

The 80 included studies were published between 2000 and 2026 (Figure 2a). Publications increased after 2012, and 55 studies (68.8%) were published between 2019 and the search date. The largest annual number was recorded in 2025, with 9 studies (11.3%). Five studies published in 2026 were included, although the count for that year was incomplete at the search date.

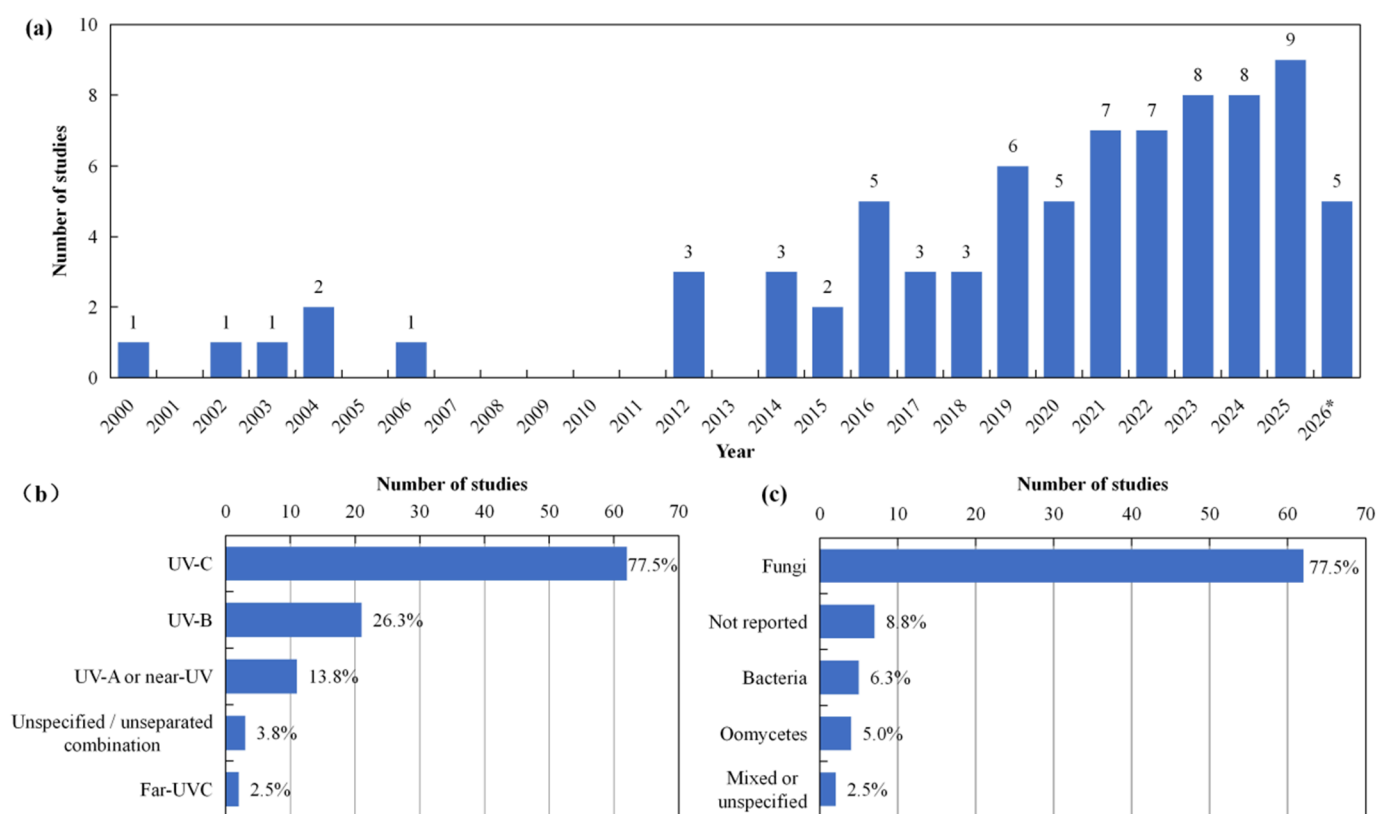


Figure 2. Characteristics of the included studies: (a) annual publication distribution, (b) UV wavebands investigated, (c) pathogen types. Note: studies involving multiple UV wavebands were counted in each applicable category; therefore, the sum of the counts and percentages in panel (b) exceed 80 studies and 100%, respectively. The 2026 count includes studies retrieved up to 25 July 2026. * The literature search was completed during 2026; the 2026 count represents a partial year.

UV-C was the most frequently investigated waveband, appearing in 62 studies (77.5%), followed by UV-B in 21 studies (26.3%) and UV-A or near-UV in 11 studies (13.8%) (Figure 2b). Three studies (3.8%) used combined or insufficiently differentiated UV wavebands. Only two studies (2.5%) investigated far-UVC, both in comparison with conventional UV-C. Because wavebands were counted non-exclusively, their total exceeded 80 studies.

Fungi were the predominant pathogen group, accounting for 62 studies (77.5%) (Figure 2c). Bacteria and oomycetes were investigated in five (6.3%) and four studies

(5.0%), respectively. Two studies (2.5%) involved mixed or unspecified pathogen groups, and seven (8.8%) did not clearly report the pathogen type.

3.3. Reporting of UV Treatment Parameters

Reporting completeness varied markedly across UV-treatment parameters (Figure 3). The treatment frequency or number of applications and wavelength were most frequently reported clearly, in 67 (83.8%) and 61 studies (76.3%), respectively. The irradiation dose and exposure duration per treatment were each clearly reported in 48 studies (60.0%). By contrast, irradiance and post-treatment light or dark conditions were clearly reported in only 29 (36.3%) and 28 studies (35.0%), respectively.

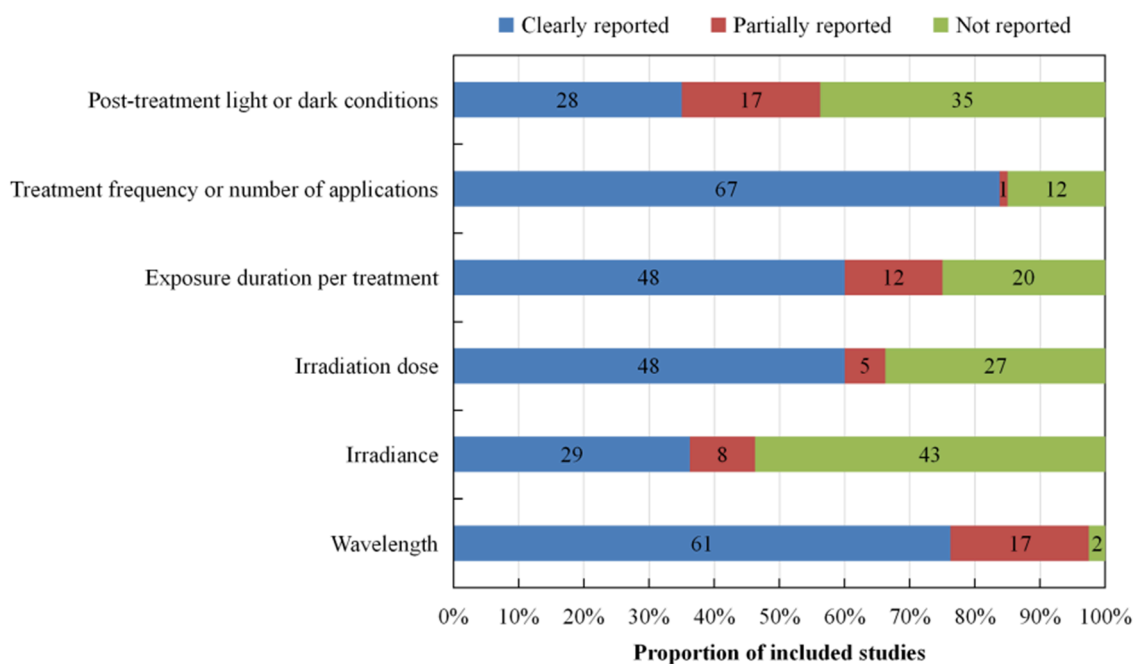


Figure 3. Reporting of UV treatment parameters.

Based on the overall completeness assessment, 27 studies (33.8%) had complete reporting, 35 (43.8%) had partially complete reporting, and 18 (22.5%) had incomplete reporting. Thus, 53 studies (66.3%) did not meet the criteria for complete reporting of the six UV treatment parameters.

3.4. Highest Validation Level and Translational Maturity

The distribution of the highest validation levels is shown in Figure 4a. Controlled-environment whole-plant experiments were the most common, accounting for 25 studies (31.3%). These were followed by greenhouse or protected-cultivation experiments (15 studies, 18.8%), in vitro pathogen or molecular-mechanism studies (13 studies, 16.3%), and field experiments (12 studies, 15.0%). A total of eight studies (10.0%) reached detached-tissue, seed, or seedling validation, and seven studies (8.8%) reached production-scale or equipment-application validation. Overall, 46 studies (57.5%) reached no higher than in vitro pathogen or molecular-mechanism studies, detached-tissue, seed, or seedling studies, or controlled-environment whole-plant experiments, whereas 34 studies (42.5%) reached greenhouse, field, production-scale, or equipment-application validation.

The distribution of translational maturity is shown in Figure 4b. Low-medium maturity was the most frequent category, accounting for 30 studies (37.5%), followed by low maturity, accounting for 20 studies (25.0%). Together, these categories comprised 50 studies (62.5%). Medium maturity was assigned to 15 studies (18.8%), high maturity to 12 stud-

ies (15.0%), and medium–high maturity to only three studies (3.8%). Thus, the evidence base remained concentrated at low to low–medium maturity, and relatively few studies provided an integrated body of evidence covering the application validation, operating parameters, and disease-control efficacy.

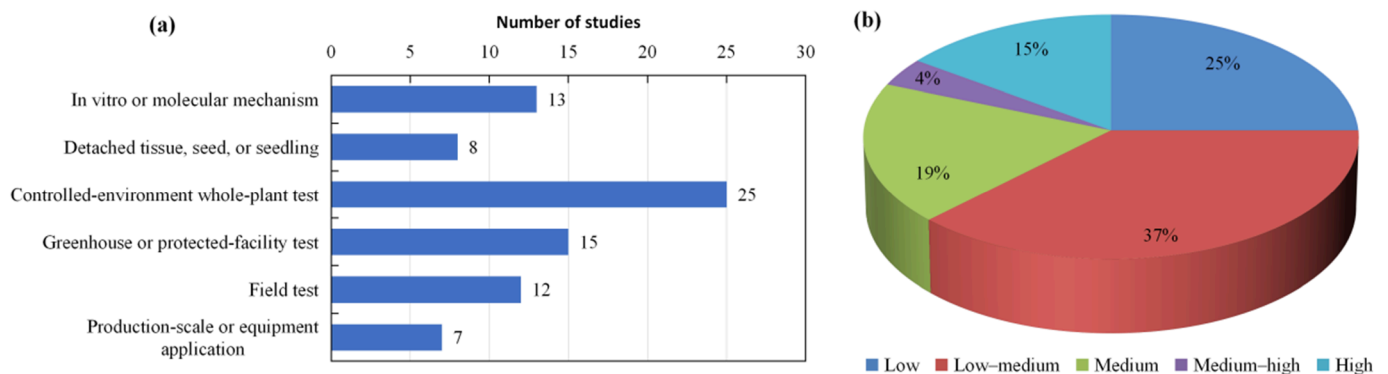


Figure 4. (a) Highest validation level and (b) translational maturity of the included studies.

The highest validation level and translational maturity represent different dimensions of evidence. The highest validation level was determined by the most advanced experimental environment or validation format reached, whereas translational maturity also incorporated disease-control efficacy, repeated or continuous treatment, dose delivery, crop safety, and equipment-performance evaluations. Production-scale or equipment-application validation should therefore not be interpreted simply as representing a higher level of biological evidence than field experimentation.

3.5. Equipment-Related Studies and Engineering Translation Characteristics

Among the 80 included studies, 11 (13.8%) were classified as equipment-related according to the prespecified criteria. These studies addressed dedicated UV irradiation equipment, mobile application platforms, automated systems, or production-scale UV applications. Engineering evidence concerning the operating parameters, dose delivery, irradiation uniformity, canopy adaptation, automatic control, and validation in application environments is summarized in Table 3.

The operating speed and target-surface dose measurement or calibration were the most frequently reported engineering indicators. The operating speed was clearly reported in eight equipment-related studies (72.7%). The target-surface dose was explicitly measured or calibrated in eight studies (72.7%), partially addressed in two studies (18.2%), and not reported in one study (9.1%). By contrast, a systematic evaluation of dose uniformity remained limited: only two studies (18.2%) explicitly evaluated dose uniformity, seven studies (63.6%) addressed it partially through the lamp arrangement, irradiance distribution, or structural design, and two studies (18.2%) did not evaluate it.

Canopy shading or reflection was explicitly evaluated in five studies (45.5%), partially addressed in three studies (27.3%), and not reported in three studies (27.3%). Automation or operational control was explicitly designed or evaluated in four studies (36.4%); six studies (54.5%) implemented only timed operation, preset speed, path planning, or other limited automation, and one study (9.1%) did not address automatic control. Regarding validation in application environments, six studies (54.5%) completed validation under greenhouse, field, or production conditions, one study (9.1%) completed only limited-scenario or prototype validation, and four studies (36.4%) did not reach validation in an actual application environment.

Table 3. Engineering evidence characteristics of the equipment-related studies ($n = 11$).

Study	Equipment/System	Speed	Target Dose	Dose Uniformity	Shading/Reflection	Automation	Validation Setting
Felek et al. (2025) [33]	Greenhouse rail-mounted UVC prototype	•	•	◐	◐	◐	Prototype greenhouse test
Mello et al. (2022) [34]	Tractor-towed semicylindrical UV-C lamp array	•	•	•	•	◐	Multi-region field validation
Skinner et al. (2022) [35]	Tractor-mounted UV-C lamp array	•	•	◐	•	◐	Two-year field validation
Suthaparan et al. (2016) [36]	Automated reciprocating UV-B lamp rack	•	•	◐	•	◐	Greenhouse validation
Gadoury et al. (2023) [37]	Tractor-towed and autonomous robotic UV-C arrays	•	•	◐	•	•	Field validation
Rea et al. (2022) [38]	Low-pressure mercury UV-C lamp output-test system	/	○	○	○	○	No application-environment validation
Onofre et al. (2021) [39]	Tractor-towed UV-C lamp array	•	•	◐	•	◐	Production-field validation
Spratling et al. (2026) [40]	Robotic mower-mounted UV-C lamp array	•	•	◐	○	•	Field validation
Bollanti et al. (2023) [41]	UV-C LED array (20 or 38 LEDs)	/	•	•	◐	◐	Laboratory engineering test
Rojas et al. (2025) [42]	Automated UV-C maize-seed treatment chamber	/	◐	◐	○	•	Laboratory prototype test
Mazar et al. (2022) [43]	Robotic task-planning system for UV treatment	•	◐	○	◐	•	Simulation only

Note: •, explicitly reported or evaluated; ◐, partially reported or evaluated; ○, not reported or evaluated; /, not applicable. Validation setting records the highest application environment reported for each study.

Overall, existing UV disease-control equipment studies have increasingly addressed the operating speed and target-surface dose delivery, but evaluations of within-canopy dose uniformity, shading and reflection effects, and operational control based on the dose actually delivered remain inadequate. Some systems have been validated under greenhouse, field, or production conditions, but few studies simultaneously provide evidence on operating parameters, dose calibration, dose uniformity, and disease-control efficacy.

4. Discussion

This study evaluated the existing evidence from four perspectives: the reporting of UV treatment parameters, experimental validation level, translational maturity, and the engineering characteristics of UV application equipment. The principal findings were as follows. Treatment frequency and wavelength were reported comparatively well, whereas irradiance and post-treatment light or dark conditions were frequently omitted. The available evidence remained concentrated in controlled experiments and at low to low-medium levels of translational maturity, indicating that a complete evidence chain from experimental efficacy to reliable production-scale application has not yet been established. Equipment-related studies frequently addressed the operating speed and target-dose specification, but

evaluations of dose uniformity within complex canopies, shading effects, and operational control remained inadequate. Collectively, these limitations constrain the reproducibility of research findings, cross-study comparisons, and engineering translation.

4.1. Incomplete Reporting of UV Treatment Parameters and Research Reproducibility

UV treatment parameters provide the basis for interpreting biological effects and reproducing experimental procedures. In this review, the treatment frequency or number of applications and wavelength were clearly reported in 83.8% and 76.3% of the included studies, respectively, whereas irradiance and post-treatment light or dark conditions were clearly reported in only 36.3% and 35.0%. Although the irradiation dose and exposure duration per treatment were each clearly reported in 60.0% of studies, a considerable proportion of studies did not provide sufficient information on target-surface irradiance or dose-determination methods. These deficiencies may limit a quantitative comparison among studies and hinder the translation of effective laboratory treatments into reproducible application protocols.

The treatment frequency, timing, cumulative dose, and background light conditions have been demonstrated to influence UV-mediated disease suppression. Suthaparan et al. [36] showed that UV-B efficacy against powdery mildew depended on the application frequency, treatment timing, dose, and reflection conditions. Other studies further indicated that the background radiation quality and daily light integral could modify the outcome of nighttime UV treatments [44,45]. Field and protected-cultivation studies on strawberry and cantaloupe powdery mildew also emphasized the importance of repeated treatment schedules and the operational timing [46,47]. Therefore, reporting only the cumulative dose without the treatment frequency and timing information is insufficient for interpreting UV treatment performance.

The wavelength is another essential parameter because biological responses vary among UV wavebands. Comparative studies have evaluated the effects of conventional UV-C, far-UVC, and UV-LED wavelengths on pathogen suppression [48–50], while action-spectrum analysis has further demonstrated wavelength-dependent differences during pathogen infection processes [51]. However, studies using commercial UV lamps as treatment tools often reported only broad categories such as UV-B or UV-C, which may limit comparisons among systems with different spectral outputs.

The actual UV dose delivered to the biological target depends not only on the exposure duration but also on the target-surface irradiance, spatial irradiance distribution, lamp arrangement, and operating conditions. Onofre et al. [39] integrated the irradiance distribution beneath a mobile UV-C array with tractor speed to estimate the delivered dose, whereas Mello et al. [34] adjusted the operating speed according to the lamp output and target dose requirements. Rea et al. [38] further demonstrated that the low-pressure mercury lamp output decreased with an accumulated operating time. These studies indicate that nominal lamp power or exposure durations alone cannot represent the actual biological dose received by the target, and a direct measurement or calibration of the delivered dose is required.

In addition, the physical characteristics of the treated object and the surrounding medium may alter UV transmission, absorption, and microbial inactivation [52,53]. Culture media, seeds, detached leaves, and intact crop canopies differ in surface structures, optical properties, orientations, and shading. Thus, the same nominal dose may correspond to substantially different doses at the pathogen surface. Studies should therefore report the irradiation geometry, measurement position, lamp-to-target distance, and relevant properties of the treated surface or medium.

Post-treatment light or dark conditions are particularly important because microorganisms may recover from UV-induced damage. Microbial recovery mechanisms and the photobiological basis of UV-induced DNA damage and repair have been extensively documented [54,55]. Janisiewicz et al. [56] found that a 4 h dark period after UV-C treatment substantially enhanced the inactivation of *Botrytis cinerea* conidia and enabled the effective control of strawberry gray mold at comparatively low doses. Recovery may also vary with the pathogen species [57–60], developmental stage [61], and the wavelength of subsequent illumination [62]. Failure to report the treatment timing, background illumination, dark-period duration, and recovery conditions may therefore confound the interpretation of wavelength and dose effects.

UV irradiation may also cause physiological responses in the crop. Supplemental UV-B has been reported to alter plant growth and gibberellin homeostasis [63], while physical treatments may influence the accumulation of metabolites such as γ -aminobutyric acid [64]. Disease-related studies further indicate that UV exposure can affect reactive oxygen species, hormone signaling, secondary metabolism [65], flavonoid accumulation [66], and defense-related gene expression [67–69]. Although these responses may contribute to induced resistance, they may also be accompanied by growth or quality changes. Crop-safety assessments should therefore extend beyond visible leaf injury to include growth, development, yield, and quality indicators where relevant.

Future studies should establish minimum reporting requirements covering the light-source characteristics, wavelength or spectral range, target-surface irradiance, measurement instrument and position, irradiation dose and its calculation method, exposure duration, application frequency and interval, lamp-to-target distance, and post-treatment light conditions. Mobile equipment studies should additionally report the operating speed, spatial irradiance distribution, calibration procedures, and deviations between target and delivered doses. Standardized reporting is necessary to improve reproducibility, support valid dose–response comparisons, and facilitate the translation of biological findings into equipment operating parameters.

4.2. Experimental Validation Scale and Evidence for Translation to Production

In this review, 46 studies (57.5%) were limited to in vitro pathogen or molecular-mechanism studies, detached-material experiments, or controlled-environment whole-plant experiments, whereas 34 studies (42.5%) reached greenhouse, field, production-scale, or equipment-application validation. In addition, studies with low or low–medium translational maturity accounted for 62.5% of the evidence base. These findings indicate that most studies have primarily demonstrated whether UV treatment can produce a biological effect, rather than whether that effect can be reproduced reliably under variable production conditions.

The available evidence extends from pathogen-sensitivity and detached-material assays to whole-plant, protected-cultivation, field, and equipment applications. In vitro and detached-material studies are useful for identifying sensitive pathogen structures, preliminary dose ranges, and possible damage or repair mechanisms. However, they do not reproduce host responses, canopy shading, environmental variability, repeated treatment, or dynamic dose delivery. Whole-plant and greenhouse experiments provide greater biological and agronomic relevance, but their results may still depend on the facility structure, crop cultivar, inoculation method, and environmental conditions.

Differences in pathogen biology further restrict direct extrapolations among experimental scales. The vegetative and reproductive structures of most powdery mildew fungi occur mainly on host surfaces [70], making them comparatively accessible to UV exposure. In contrast, gray mold can infect flowers, fruits, and wounded tissues, and the pathogen

may occur within the canopy or in concealed tissue sites [71–73]. Downy mildews have internal leaf-infection stages, although sporulation is commonly concentrated on the abaxial leaf surface [74,75]. Consequently, the same nominal UV dose may produce different disease-control outcomes depending on the pathogen location, infection stage, irradiation direction, and target accessibility.

In vitro pathogen sensitivity therefore cannot be assumed to represent disease-control performance in actual host tissues [76]. In grapevine systems, nighttime UV treatment produced different levels of control against powdery mildew, downy mildew, and bunch rot [37,77]. These findings show that successful pathogen inactivation under simplified conditions does not necessarily predict effective disease suppression when infection sites are concealed or when the host–pathogen interaction is more complex.

The canopy architecture introduces an additional translational constraint. The organ distribution, canopy porosity, leaf orientation, and local microclimate affect both disease development and the optical accessibility of the target [78]. Research on crop lighting has also shown that identical mean light inputs can generate markedly different leaf-level light distributions when the lamp position changes [79]. Thus, treatments applied to flat culture media, single leaves, and intact crop canopies cannot be considered equivalent solely because their nominal doses are the same.

Several studies have nevertheless demonstrated that UV treatment can be translated into field protocols. Onofre et al. [39] showed, in multi-season trials on commercial and research strawberry fields, that repeated nighttime UV-C treatments could achieve or exceed the control effectiveness of conventional fungicide regimes against powdery mildew. In the Florida field trial of Mello et al. [34], twice-weekly UV-C treatment reduced powdery mildew incidence on strawberry fruit to 4.5%, compared with 25.8% in untreated controls; no visible phytotoxicity or reduction in fruit yield was reported under the tested conditions. In contrast, UV-C treatment in the cucumber field trials of Skinner et al. [35] slightly delayed the onset of downy mildew but did not reduce its subsequent rate of progression. Subsequent evaluations in different production regions by Mello et al. [34] required different operating speeds to achieve the same target dose, highlighting the need for location- and equipment-specific calibration. In grapevine trials, Gadoury et al. [37] reported no detectable phytotoxicity or reductions in the yield and quality parameters assessed under the tested UV-C-treatment schedules. Vineyard trials by McDaniel et al. [80] further demonstrated that production validation should assess fruit quality and crop safety together with disease suppression.

Future research should therefore prioritize representative crop–pathogen systems and establish continuous evidence chains from controlled dose screening to whole-plant, greenhouse, and multi-site field validation. Evaluations should include disease control, crop injury, yields, quality, recurrence, operational efficiency, energy consumption, and economic cost. High translational maturity should be assigned only when biological efficacy, crop safety, dose stability, and engineering feasibility have been demonstrated jointly.

4.3. Dose Delivery and Control in UV Application Equipment

This review identified 11 equipment-related studies. Of these, eight explicitly reported the operating speed and eight explicitly measured or calibrated the target-surface dose, indicating that existing equipment research has paid considerable attention to mobile operation and target-dose specification. However, only two studies explicitly evaluated dose uniformity, whereas seven addressed it only indirectly through the lamp arrangement, irradiance distribution, or structural design. Automation or operational control was explicitly evaluated in only four studies, while another six were largely limited to timed operation, a preset speed, or path control. These findings indicate that the ability of equipment to

move automatically is no longer the sole engineering issue. The central challenge is how to deliver an effective and safe dose reliably within complex crop canopies.

The identified equipment included greenhouse rail-mounted systems, tractor-mounted or tractor-towed lamp arrays, autonomous mobile platforms, UV-C LED arrays, enclosed seed-treatment devices, and robotic task-planning systems (Table 3). Although these configurations demonstrate the technical feasibility of mechanized UV application, their evaluations differed substantially in disease-control validation, dose measurement, spatial uniformity, and operation under production conditions.

Canopy shading can produce substantial differences between nominal and actual delivered doses. Suthaparan et al. [36] used a mobile UV-B lamp rack to investigate the effects of reflective materials and leaf disturbance on disease control. Reflective surfaces improved treatment efficacy in shaded areas, whereas airflow-induced leaf movement did not further improve control and may even have reduced efficacy by promoting spore dispersal. These results indicate that increasing lamp power or introducing mechanical disturbance cannot, by itself, resolve canopy-shading problems. The lamp position, angle of incidence, reflective structures, and crop-canopy architecture must be considered in an integrated design.

Changes in light-source output are another major cause of deviation between the target and actual dose. Rea et al. [38] found that the output of low-pressure mercury lamps used for agricultural UV treatments declined with an accumulated operating time. Bollanti et al. [41] tested the irradiation performance of different UV-C LED-array configurations and showed that the LED number, arrangement, and working distance all affected target-surface output. Rojas et al. [42] incorporated operational monitoring into a seed-treatment system, although the dose-control conditions in such an enclosed treatment environment differ from those in open crop canopies. Equipment-rated power should therefore not replace the periodic measurement of target-surface irradiance. Lamp aging, temperature, power-supply conditions, and other factors should also be incorporated into calibration procedures.

As with other crop-protection machinery, platform operating parameters should be evaluated together with the treatment actually delivered to the target [81,82]. Zhang et al. [83] reported that unstructured terrain, wheel slip, and dynamic disturbances were major causes of reduced path-tracking accuracy in unmanned agricultural ground vehicles. For mobile UV equipment, path deviation changes not only treatment coverage but also the lamp-to-canopy distance and local exposure duration, thereby causing spatial fluctuations in the delivered dose. Independent measurement is also necessary because onboard records may not fully represent instantaneous changes in travel trajectory and speed [84]. Field systems that incorporate measured operating parameters into dose calibration therefore provide a more reliable basis for UV application [34,39].

Overall, most existing systems lack a closed-loop mechanism capable of adjusting the speed or lamp output in real time in response to lamp degradation, the canopy height, or the measured dose. Future equipment evaluations should not be limited to reporting the lamp number, rated power, and operating speed. They should also measure dose distributions at the top, sides, shaded surfaces, and interior of the canopy. In addition to the mean dose, studies could report dose variability, the proportion of the target area receiving less than the effective-dose threshold, and the proportion receiving more than the crop-safety threshold. Control systems should progressively adopt a closed-loop architecture consisting of irradiance monitoring, actual-dose estimation, and speed or power adjustments, thereby maintaining stable dose delivery despite changes in the light-source output and canopy structure.

4.4. Translation of Biologically Effective Doses into Equipment Operating Parameters

A substantial disconnect remains between biological experiments and equipment-related research. Plant-pathology studies generally describe UV treatment in terms of the irradiance, exposure duration, or irradiation dose, whereas equipment studies more commonly use the operating speed, lamp power, number of operations, and travel path. Without a quantitative relationship between these two sets of variables, an effective dose identified in laboratory experiments cannot be translated directly into an executable equipment-operating protocol.

The definition of a biologically effective dose varies with the biological endpoint. Some studies determine efficacy from direct pathogen responses, including spore germination and mycelial growth [85], differences between conidia and hyphal fragments [86], germicidal effects on epiphytic fungi [87], and photolyase-mediated recovery from UV-induced damage [59,88]. Other studies define efficacy primarily through induced host resistance, including resistance to wheat leaf rust and powdery mildew [89], UV-B-induced resistance in cucumber [90], the regulation of reactive oxygen species, hormones, and terpenes in strawberry [65], the upregulation of pathogenesis-related genes [67], UVR8-mediated defense [68], and transcriptomic changes in tomato defense and stress-response pathways [91]. Because direct pathogen inactivation and host-mediated resistance involve different mechanisms, their effective-dose thresholds and optimal treatment timings should not be treated as interchangeable.

A practical translational pathway should comprise three consecutive stages. First, the biologically effective dose range should be determined for a specific crop–pathogen system under controlled conditions, including both the lower boundary associated with inadequate disease suppression and the upper boundary associated with crop injury. Second, the stability of this range should be validated in whole-plant, greenhouse, and field experiments under different canopy structures, environmental conditions, treatment timings, and crop developmental stages, thereby defining a crop-safe and disease-effective dose window. Third, this dose window should be translated into controllable equipment parameters, including the lamp output, operating speed, lamp-to-target distance, application frequency, and travel path, and verified using measurements of the actual delivered dose.

This translation cannot be based on the cumulative dose alone. Under the same cumulative UV-B dose, Suthaparan et al. [36] compared different combinations of irradiance, treatment durations, and application frequencies and found that multiple combinations significantly suppressed powdery mildew, indicating that identical cumulative doses do not necessarily represent identical treatment protocols. In cucumber, higher UV-C doses or excessively frequent applications suppressed powdery mildew but could also reduce the leaf area, whereas lower daily doses or longer treatment intervals produced different balances between disease control and plant growth [92]. Equipment optimization should therefore consider the irradiance per treatment, exposure duration, application interval, treatment timing, crop safety, and operational efficiency rather than simply maximizing the cumulative dose.

The crop cultivar and developmental stage may also alter the safe-dose window. Forges et al. [93] compared the sensitivity of different strawberry cultivars to gray mold after UV-C treatment, showing that the same treatment regime may produce different outcomes among cultivars. De Oliveira et al. [94] found that preharvest UV-C induced physiological, biochemical, and transcriptional changes in strawberry. Montalbán et al. [95] evaluated the effects of pre-flowering UV-B and UV-C treatments on tomato growth, flowering, and defense. McDaniel et al. [80] simultaneously examined the effects of UV-C on powdery mildew and fruit quality in vineyards. A safe-dose window should therefore not be

determined solely from a single cultivar, a single developmental stage, or short-term visible injury.

Based on the findings of this review, future studies should establish a standardized evidence chain: comprehensively report treatment parameters, screen appropriate wavelengths and determine biologically effective doses, validate the crop-safe dose window, measure the actual dose distribution within the canopy, and then translate the target dose into equipment operating parameters. Such a pathway would reduce the current separation between biological experimentation and equipment development and improve the efficiency with which research findings are translated into production applications.

A limitation of this review is the substantial heterogeneity in crop–pathogen systems, UV treatment protocols, experimental settings, and reported outcomes, which precluded a quantitative meta-analysis.

5. Conclusions

This systematic review synthesized 80 studies on UV-based crop disease control and evaluated their reporting completeness, validation level, translational maturity, and engineering characteristics. The evidence confirms that UV treatment can suppress plant pathogens directly and enhance host defense, but its effects depend strongly on the wavelength, irradiance, dose, treatment frequency, timing, post-treatment light conditions, crop–pathogen characteristics, and target accessibility. Only 33.8% of the included studies completely reported the six assessed treatment parameters, while most evidence remained at low or low–medium translational maturity. The reporting-completeness assessment measured whether six UV-treatment parameters were documented; it did not assess treatment efficacy. Translational maturity summarized the extent of application validation and supporting evidence, rather than establishing that a treatment was effective and crop-safe across production settings. Field studies and the 11 equipment-related studies included in this review provide evidence that UV treatment can be applied in field and production settings. However, evidence from equipment-related studies remains limited, and dose uniformity, canopy shading, lamp-output variation, crop safety, and feedback-based control require further evaluation. Future research should establish standardized parameter-reporting requirements and continuous validation pathways linking controlled biological experiments with greenhouse, multi-site field, and production-scale applications. In particular, biologically effective and crop-safe dose windows should be converted quantitatively into executable parameters, including the lamp output, operating speed, lamp-to-target distance, treatment interval, and travel path, and verified through actual delivered-dose measurements. Integrating biological efficacy, crop safety, the spatial dose distribution, equipment performance, and closed-loop control is essential for developing reproducible, controllable, and scalable UV-based crop disease-management systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16202258/s1>, File S1: Table S1: Database search summary and complete search strategies; File S2: Table S2: Characteristics and evidence classifications of the included studies; Supplementary File S3: PRISMA 2020 checklist. References [33–51,56–62,65–69,77,80,85–131] are cited only in Supplementary Table S2.

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Abbreviations

The following abbreviations are used in this manuscript:

UV	Ultraviolet
UV-A	Ultraviolet A
UV-B	Ultraviolet B
UV-C	Ultraviolet C
Far-UVC	Far-ultraviolet C

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