

Review

Hail Netting in Apple Orchards: Current Knowledge, Research Gaps, and Perspectives for Digital Agriculture

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Abstract

Hailstorms are a major climatic threat to apple production, causing substantial economic losses in orchards worldwide. Anti-hail nets have been increasingly adopted to mitigate this risk, but the scientific literature on their effectiveness and future applications remains scattered, especially considering advances in digital agriculture. This study synthesizes current knowledge on the use of anti-hail nets in apple orchards through a systematic review and explores future perspectives involving digital technologies. A PRISMA-based review was conducted using three databases, revealing information regarding the studied countries, netting colors, and apple varieties, among others. A clear research gap was identified in integrating anti-hail nets with remote sensing and Artificial Intelligence (AI). This paper also analyzes studies from Vacaria, Brazil, a key apple-producing region and part of the Semear Digital project, highlighting local efforts to use hail netting in commercial orchards. Potential applications of AI algorithms and remote sensing are proposed for hail netting assessment, orchard monitoring, and decision-making support. These technologies can improve predictive modeling, quantify areas, and enhance precision management. Findings suggest combining traditional protective methods with technological innovations to strengthen orchard resilience in regions exposed to extreme weather.

Keywords: PRISMA; *Malus domestica*; climate; extreme weather; remote sensing; machine and deep learning



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1. Introduction

Apple (*Malus domestica*) production is highly susceptible to climatic adversities, especially hailstorms, which can cause significant damage to fruits, reduce yield quality, and lead to substantial economic losses [1,2]. In regions where hail incidence is frequent, such as in temperate and subtropical zones, the adoption of protective strategies has become essential for maintaining crop viability and market standards [1,3].

Among these strategies, the use of hail nets has gained prominence as a physical barrier that protects orchards from direct hail impact. However, the effects of these nets go beyond

mechanical protection. Several studies have investigated how hail nets, depending on their color, mesh size, and material, can alter microclimatic conditions within the orchard [2,4–6]. These modifications may influence temperature, light diffusion, humidity, and airflow, thereby affecting fruit coloration, maturation, pest behavior, and even disease incidence. The effects on the microclimate become even more pronounced when hail nets remain permanently closed over orchards, a situation frequently observed in Brazil.

Unlike other temperate regions of the world, where winter snowfall requires opening and closing the nets at different times of the year, in Brazil, hail nets are kept permanently closed throughout the year, including winter. This further impacts the microclimate factors beneath the nets and the albedo of the areas. Although Brazilian studies describe the methodology of anti-hail net installation as continuously maintained canopies [7,8], none of them explicitly highlight this practice as a distinctive feature. This characteristic, however, has been consistently confirmed in field observations, where hail nets remain closed throughout the entire year, including the winter season.

These changes are particularly important in the context of fruit quality and commercial value, as factors such as color uniformity, size, firmness, and sugar content play a crucial role in market acceptance [9]. Additionally, the indirect effects of hail nets, such as changes in pest and pollinator activity, require a better understanding to ensure integrated orchard management. This makes hail netting not only a protective but also a management-enhancing technology, especially when combined with other strategies.

In addition to physical protection, hail nets are part of a broader climate adaptation strategy in fruit production systems. This scenario highlights the importance of integrating protective structures with tools that enhance climate monitoring and risk forecasting for small and medium-sized producers, who often face greater vulnerability to climate risks and resource limitations [10,11]. Other types of netting systems are also used to mitigate hailstorm damage, despite having distinct primary functions such as light filtration or pest exclusion.

In this context, digital agriculture technologies based on Remote Sensing and Artificial Intelligence (AI) offer innovative tools to monitor orchard conditions, support decision-making, and optimize the use of protective structures [12]. These technologies can be used to assess orchard health, predict pest outbreaks, or evaluate spatial variability in microclimate, providing valuable insights for more efficient and sustainable management.

In the context of global apple production, Brazil contributes with an average annual output of over one million tons [13,14]. Among the key producing regions, the municipality of Vacaria, located in the state of Rio Grande do Sul, stands out as a major hub for apple cultivation. This region has been the focus of several studies involving the application of hail netting techniques, reflecting both the agricultural importance of the area and its vulnerability to hailstorms [15]. Due to its structured orchards and ongoing research initiatives, Vacaria also presents a promising landscape for the integration of advanced digital agriculture technologies. These tools have the potential to optimize orchard monitoring, climate risk management, and decision-making, positioning the region as a strategic environment for innovation in apple farming.

Despite these advancements, a gap remains in the literature regarding the integration of digital tools with studies on hail netting in apple orchards. Therefore, this study aims to (i) conduct a systematic PRISMA-based review of scientific articles addressing the use of hail nets in apple orchards; (ii) analyze studies carried out in the municipality of Vacaria (Brazil), a strategic location within the “Semear Digital” project; and (iii) identify future perspectives and potential applications of AI, Remote Sensing, and other digital agriculture tools that can contribute to the effective use of hail nets in apple production.

2. Materials and Methods

The methodological approach is illustrated in a flowchart showing the three main stages of the research (Figure 1). The first stage consisted of a systematic review conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, encompassing database selection, search strategy definition, and article screening and eligibility assessment. The second stage focused on a targeted analysis of studies carried out in Vacaria, Brazil, highlighting local research on hail netting in apple orchards and its connection with the Semear Digital project [16]. The third stage explored potential applications of remote sensing (RS), machine learning (ML) and deep learning (DL) in apple orchards, particularly for orchard monitoring and decision-making support. This workflow ensured a comprehensive synthesis of existing knowledge while identifying research gaps and opportunities for technological integration.

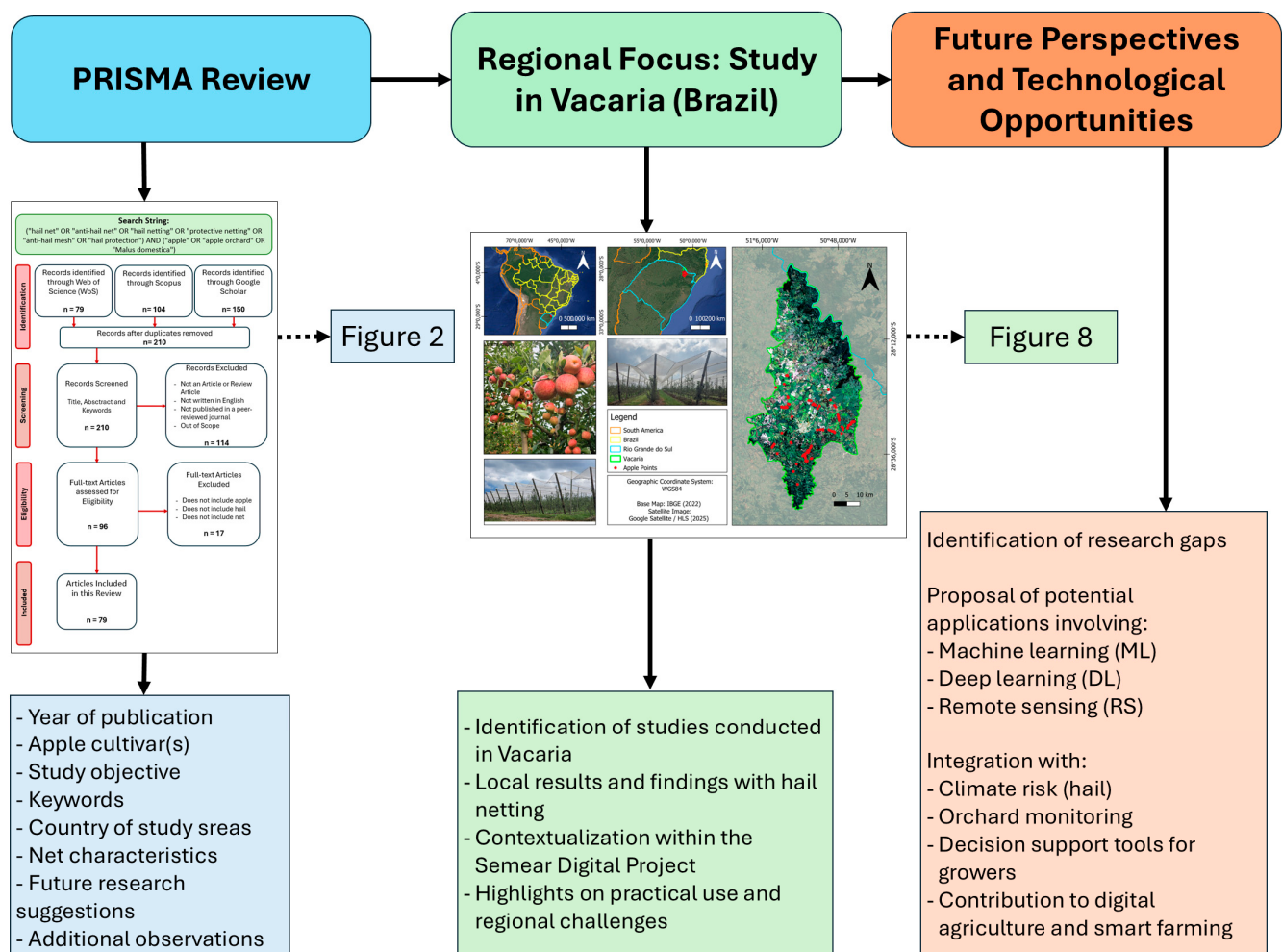


Figure 1. Flowchart of the study illustrating the three main stages. The first stage involved a systematic review using the PRISMA methodology. The second focused on an analysis of existing studies conducted in Vacaria (Brazil), a region included in the Semear Digital Project. The third stage explored future perspectives, highlighting potential applications of AI (including machine learning and deep learning) and remote sensing technologies in the context of hail netting in apple orchards.

2.1. PRISMA Review

This review followed the PRISMA guidelines [17–19] and was based on a structured literature search conducted in three databases: Web of Science (WoS), Scopus, and Google Scholar. The following search string was used in all platforms: ("hail net" OR "anti-hail net" OR "hail netting" OR "protective netting" OR "anti-hail mesh" OR "hail protec-

tion") AND ("apple" OR "apple orchard" OR "Malus domestica"). The review was conducted in July 2025 and included studies from all available years, without imposing any temporal restrictions.

The search was initially performed in Web of Science, returning 127 records, followed by Scopus with 151 records. For Google Scholar, the first 150 results were considered, based on relevance and comparison with results from the other databases (Figure 2).

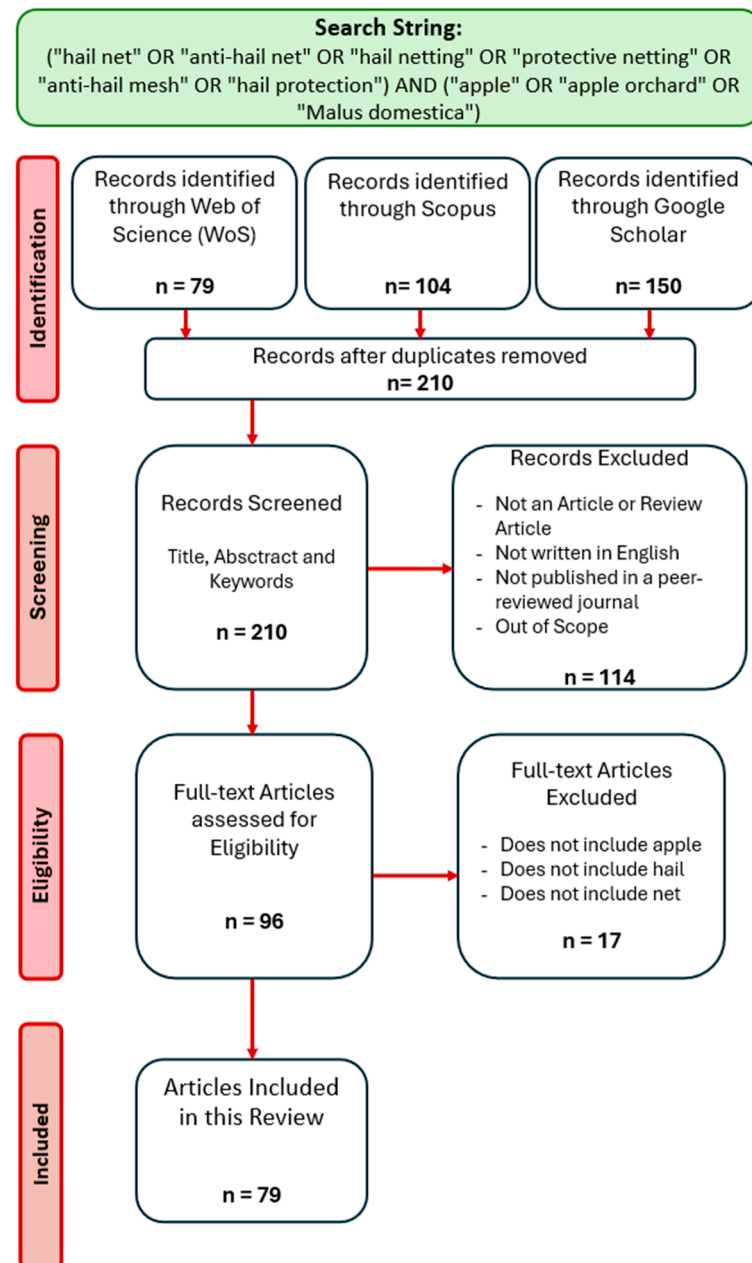


Figure 2. PRISMA flow diagram showing the identification, screening, eligibility, and inclusion process based on three databases (Web of Science, Scopus, and Google Scholar). The selection focused on studies investigating the use of hail nets in apple orchards.

After applying filters for Article and Review Article types and restricting the language to English in WoS and Scopus, the number of records was reduced to 79 and 104, respectively. Duplicate records across the three databases were then removed, resulting in 210 unique articles for initial screening.

An initial screening was performed on these 210 articles based on titles, abstracts, and keywords. Despite the filtering, many out-of-scope studies still appeared in the results. Therefore, articles were excluded if they:

- Were not articles or review articles;
- Were not written in English;
- Were not published in peer-reviewed journals;
- Were clearly out of scope (e.g., studies on grapes, kiwi, pears, or other unrelated fruits).

This step excluded 114 records, leaving 96 articles for full-text eligibility assessment.

During the eligibility phase, the full texts were reviewed to determine whether the studies focused on apple orchards using hail nets. Additional terms such as photoselective nets, protective nets, and exclusion nets were also accepted if the articles clearly indicated that these nets were applicable or useful for hail protection, despite their primary focus on pest control or solar radiation management.

After applying the eligibility criteria, 79 articles remained:

- 46 articles from WoS;
- 24 unique articles from Scopus (not present in WoS);
- 9 unique articles from Google Scholar (not present in WoS or Scopus).

After selecting the 79 articles, information regarding the countries of the study area, year of publication, netting colors, apple varieties investigated, and other relevant details was analyzed. Only the studies retrieved through the systematic search string were considered, ensuring that the results strictly reflect the PRISMA filtering process.

2.2. Regional Focus: Study in Vacaria (Brazil)

Vacaria, located in the state of Rio Grande do Sul, Brazil, is one of ten Agrotechnological Districts (DATs) selected as part of the “Center for Development in Digital Agriculture (CCD-SemeAr)” project [16]. The initiative is led by Embrapa Digital Agriculture, (one of 43 research centers of the Brazilian Agricultural Research Corporation) in collaboration with six other institutions. The SemeAr Digital Project aims to foster the adoption of digital technologies to sustainably increase agricultural productivity, especially among small and medium-sized producers.

Although remote sensing and AI represent promising approaches for providing a more systemic view about the effects of hail netting in apple orchards, the PRISMA review did not identify any studies that applied these techniques specifically for this purpose.

Of the 79 articles selected in the PRISMA review, five were conducted in Vacaria. These were the first to be reviewed to identify challenges relevant to the SemeAr Digital project, as well as to other countries with similar needs regarding the use of hail netting for apple cultivation. This local analysis also supports the third phase of the study, which outlines future perspectives for the application of remote sensing and AI in this field.

2.3. Future Perspectives and Technological Opportunities

This final stage was structured according to the research gaps revealed by the PRISMA review and insights from previous studies carried out in Vacaria. The PRISMA review did not reveal any articles applying AI, and identified only one study involving remote sensing. This gap highlights how future studies can help fill this gap and offer practical contributions to growers facing similar challenges.

In this context, the study outlines potential applications involving ML, DL, and remote sensing, with a focus on enhancing climate risk analysis (for hail events), orchard monitoring, and decision support tools for producers. This integrative approach aims to foster the development of digital agriculture and smart farming, especially in regions like Vacaria and other areas with similar needs.

3. Results and Discussion

3.1. PRISMA Review

To highlight the main topics explored in the reviewed studies, a word cloud was created using the keywords provided by the authors. As shown in Figure 3, the size of each term is proportional to its frequency in the dataset. Notably, terms such as *Malus domestica*, management, antihail, fruit, apple, light, and net were the most frequent. These results reinforce the central role of hail netting in apple orchard management and its impact on fruit quality and environmental conditions within the production system.

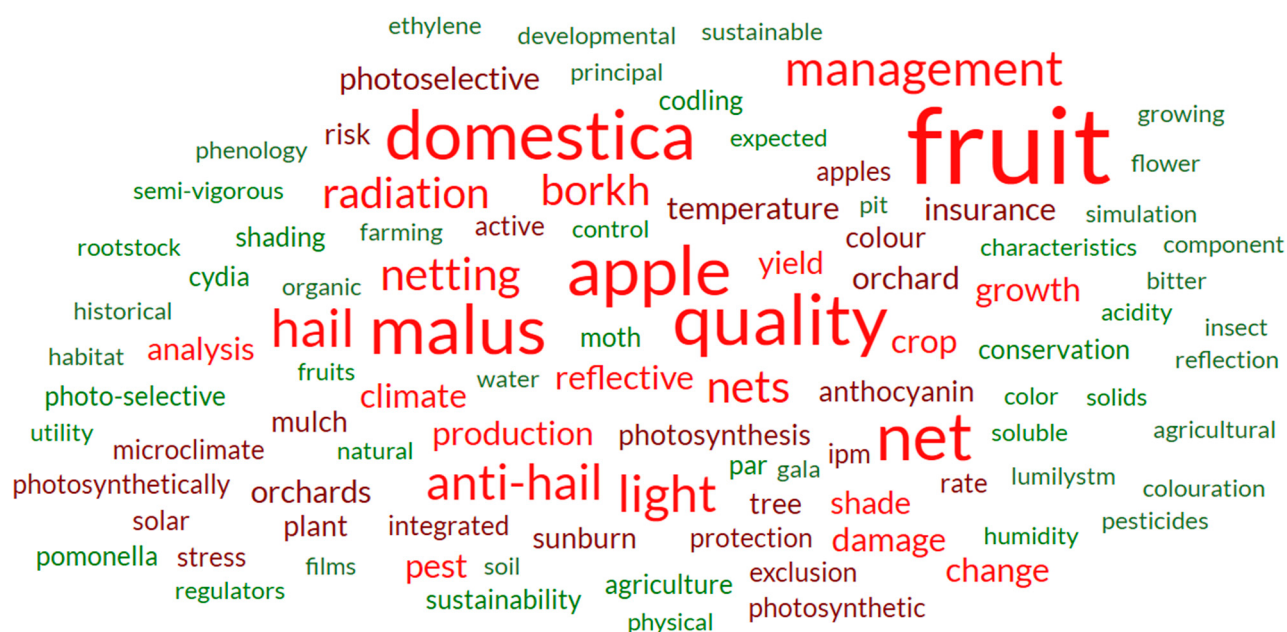


Figure 3. Word cloud generated from the keywords of the reviewed articles. The size of each word is proportional to its frequency across the studies.

Figure 4 shows the temporal distribution of articles related to the use of netting in apple orchards from 2002 to 2025. While early publications were sparse and irregular, with only one or two articles per year up to 2013, a noticeable increase in scientific output began in 2016. Significant increases were observed in 2016 and 2018, with seven articles each, reflecting growing research interest. The highest number of publications occurred in 2022, with 11 studies, followed by 2020 with nine. This surge may be attributed to technological advances in netting materials, the increased frequency of extreme weather events, and the broader adoption of sustainable farming practices.

Table 1 provides an overview of the main research objectives identified across the reviewed literature. It also presents the number of articles that addressed each objective and lists the most frequently studied information associated with them. This structured compilation not only offers insights into the predominant directions taken by current research on hail netting in apple orchards but also facilitates the identification of underexplored areas. By organizing this information in a comparative manner, the table contributes to a better understanding of how different aspects of apple production, such as fruit quality, microclimate management, pest control, and physiological responses, have been approached in the scientific literature, ultimately supporting the formulation of future research priorities. The third column, “Identified Information”, presents the specific variables, elements, or measurements investigated in each study. It is important to note that a single article may appear in more than one category in the first column, depending on the scope of its objectives. However, the information presented in the third column was organized according to the

objective-based categories, rather than by thematic classification of variables or elements, as the aim was to highlight which data and information were addressed within each objective. The adopted categories were Atmosphere, Climate, Plant, Soil, Water, and Other. This categorization allows for a clearer visualization of the different variables addressed across the studies.

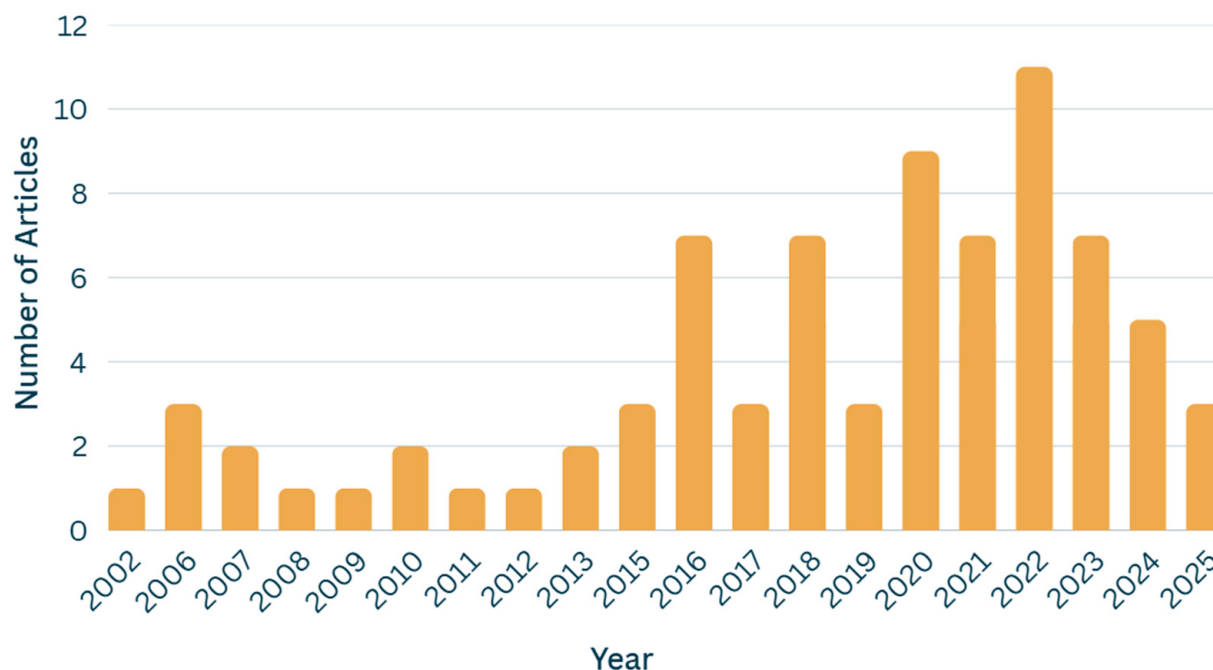


Figure 4. Number of articles published per year in the reviewed literature.

Table 1. Summary of the main research objectives addressed in studies on hail netting in apple orchards, including the number of articles per objective and the most frequently studied variables associated with each focus area.

Study Objectives	Number of Articles	Identified Information
Microclimate/light management/solar radiation/sunburn	29	Atmosphere: [air temperature, humidity (air, relative), wind (parameters, speed)] Climate: [geomorphological, light (interception, spectra assessment, spectral composition), microclimatic, Photosynthetically active radiation (PAR), photon flux density, precipitation, radiation (net, photosynthetically, solar), sunburn, temperature (bark, canopy, dew point and the wet-bulb, fruit surface, heat index, maximum and minimum), thermographic imaging, weather] Plant: [acoustic pressure, anatomical and physiological variables, angle, anthocyanins, area, biotic and abiotic stresses, carbohydrates and organic acids, chemicals, chlorophylls and carotenoids, disease, distance, dry matter, force (delta, final, linear distance, max, mean, ratio, yield), fruit (color, fruit set, growth, pests, pigment, quality, skin, trees), harvest, leaf (area index, cuticle, micromorphology, pests, stomatal conductance, thickness, thinning, water potential), material, net carbon assimilation rate, pest, pesticide, phenol, phenology, photochemical (efficiency, reflectance Index—PRI), plant architecture and potential irradiation, pruning and dormant sprays, quantum yield, reflective mulches and biostimulants, shoot, soluble solids, weed] Soil: (moisture, soil temperature) Other: (caliper, correlation, sensitivity, statistical)
Fruit quality	27	Atmosphere: [air temperature, humidity (maximum and minimum relative, air)] Climate: [light (supply, measurement, intensity, quality), meteorological, precipitation, sunburn, temperature (maximum, minimum and average)] Plant: [acid (ascorbic, chlorogenic, organic, titratable), anthocyanin, antioxidant activity, area, aroma volatile, attributes (chemical, physical, sensory), branch, canopy, carotenoids, chlorophylls (fluorescence, relative content, spectrophotometric determination), crop production, distance (linear, peaks), epicatechin and procyanidin B1, flavonoid, floridizine, force (delta, final, linear distance, max, mean, peaks, ratio, yield), fruit (damage, diameter, diseases, firmness, hardness, hue angle, length, luster, mass, maturation, number, physiological disorders, size, surface temperature, weight, yield), growth (new shoot, plant), intercellular CO ₂ concentration, leaf (area index, relative water content, thickness), liquid chromatography/tandem mass spectroscopy, phenolic (individual, total), photosynthetic rate, physicochemical, pressure (mean and max acoustic), ripening, seed, skin color (intensity, coverage), soluble solids, starch, sugar (composition, core index, core fruit rate, soluble, total), transpiration rate, trunk, volatile compounds, yield (quantum)] Soil: (soil temperature) Other: (statistical evaluation, storage conditions)

Table 1. Cont.

Study Objectives	Number of Articles	Identified Information
Pest/insect and disease control	14	Atmosphere: (air temperature) Climate: [climate, temperature (habitat, surface)] Plant: [apple maggot (<i>Rhagoletis pomonella</i>), arthropod, codling moth (<i>Cydia pomonella</i>), disease (intensity, management, progress curve, severity), drivers of flower-visiting insects, foliar insects, fruit (damage caused by pests, quality), insecticide spray, larval damage, mites, non-parasitic damage, nutraceutical analysis, pesticide, phenology, plant architecture and potential irradiation, plant materials, post-harvest rots and bitter pit, pruning and dormant sprays, sampling of insects, symptom, thinning, weed control, yield] Soil: (soil management) Water: (water management) Other: [developmental rates, economic, farmers' awareness of organic apple production, farmers' knowledge and perceptions, farm and farmer characteristics, final knock-down treatment, hail net cost, pest management practices, sensitivity analysis, statistical analysis, tethered virgin females, trapping (calling females, pan sampling, synthetic pheromone)]
Yield and production	13	Atmosphere: (air humidity, air temperature, wind) Climate: [light (intensity, quality), micrometeorological conditions, meteorological, net radiation, PAR, temperature (maximum, minimum)] Plant: [canopy, chlorophyll fluorescence, diameter, firmness, fruit (chemistry, color, diameter, number, quality, shape, set), growth, height, hue angle, leaf (relative water content, area), length (fruit and branch), mass, organic acids, phenolic, plant materials, productivity, shoot growth, soluble solids, titratable acidity, trunk cross-section area, yield (efficiency, per tree, total, high-quality, quantum)] Soil: (soil temperature) Water: (leaf relative water content) Other: (principal component, statistical analysis) Atmosphere: [humidity (maximum and minimum)] Climate: (degree days, PAR, precipitation, temperature)
Physiological responses	9	Plant: [acidity, antioxidant, chemicals, chlorophyll fluorescence, chlorogenic acid f, color-intensity, epicatechin and procyanidin B1, floridizine, fruit (firmness, weight, colour, maturation, quality), hue angle (h°), iodine-starch index, leaf (area index, gas exchange, water status, biochemical, ionome), phenolic compounds, phenology, physicochemical attributes of the fruit and harvest, plant material, QY (quantum yield), sclerophylly indexes, soluble solids, starch conversion, stomatal conductance, transpiration] Soil: (glomalin-related soil proteins) Water: (leaf water status) Other: (sensitivity analysis, statistical analysis, storage conditions and variables)
Coloration improvement	8	Climate: (climate conditions, light, sunburn) Plant: [generative, fruit (colouration, quality, ripeness parameters, skin, surface temperature, trees), phenols (total, individual), spectrophotometric determination of chlorophylls and carotenoids, vegetative] Other: (reflective mulches and biostimulants, statistical evaluation)
Water use and irrigation	6	Climate: (microclimatic, temperature, thermographic imaging, weather and irrigation) Plant: [dry matter content, fruit (element content, growth, maturity, quality, weight), leaf (element content, gas exchanges, transpiration rate, water potential), physiology, pigment content, spectrophotometric determination of chlorophylls and carotenoids, yield/production] Water: (water savings) Other: (net treatments, statistical analysis)
Risk analysis and insurance	4	Climate: (altitude range) Plant: [planted area, quality (normal conditions, reduction, market price), yield (data, reduction)] Soil: (slope interval) Other: (cost, economic, insurance, price, spatial location, wealth data)
Quality/economic losses	3	Atmosphere: (humidity) Climate: (altitude range, light intensity, temperature) Plant: [determination of photosynthetic rate, flavonoid, fruit (weight, shape index, luster, sugar core rate), intercellular CO₂ concentration, leaf (thickness, area and chlorophyll), phenol, quality (parameters, fruit, yield), soluble sugar, titratable acid, transpiration rate, vitamin C] Soil: (hardness, slope)
Impact of insecticides/pesticide	3	Plant: (Insecticide spraying, Net $\times$ Spray interaction, Yield and quality data) Other: [analytical methods, cost, dermal contamination, economic, inhalation, larval damage, marketable, predator family (Richness, abundance, diversity), statistical analysis, trapping (synthetic pheromone, females)]
Pollination and biodiversity	3	Plant: (apple variety on breeding success, breeding density, length of hedgerows, tree height, tree pruning, % herbicide) Soil: (% bare soil) Water: (% droplet) Other: (effect of predation, elevational span, model species, nest-support, % covered by nets, % of rows)
Soil and leaf traits	2	Climate: (microclimatic) Plant: [chlorophyll fluorescence, element content—leaves and fruit, growth, leaf (gas exchange, water status, biochemical analysis, ionome), material, production and fruit weight, Sclerophylly indexes, yield] Soil: (Glomalin-related soil proteins) Other: (statistical analysis)

A thematic analysis of the reviewed studies reveals a predominant focus on micro-climate management and fruit quality (29 and 27 studies, respectively). This reflects the central role that environmental factors and fruit characteristics play in the evaluation of hail netting systems in apple orchards. In the microclimate/light management/solar radiation/sunburn category, researchers frequently measured variables such as air temperature, soil temperature, humidity, and light intensity, as well as sunburn incidence and canopy

conditions. These parameters are crucial for understanding how hail nets affect the orchard microenvironment and mitigate extreme weather impacts, particularly in regions susceptible to hailstorms and intense solar radiation.

In the fruit quality category, an extensive range of variables was identified, highlighting the complexity and multidimensional nature of this research objective. Studies examined not only external attributes such as skin color, fruit size, and firmness but also internal quality factors including total soluble solids (TSS), acidity, sugar content, flavonoid and phenolic compounds, and chlorophyll levels. Some studies also applied advanced methods like spectrophotometry and chlorophyll fluorescence to assess biochemical and physiological traits of the fruit. This comprehensive assessment demonstrates the strong interest in how protective netting may influence the nutritional and marketable attributes of apples, with implications for both consumer appeal and post-harvest quality.

The third most frequent category was pest/insect and disease control, with 14 studies. These investigations explored not only the incidence and severity of specific diseases, such as *Glomerella* Leaf Spot (GLS), but also pest behavior, insect trapping techniques, and pest management practices. Hail netting was assessed not only for its protective function against hail but also for its role as a physical barrier that alters pest dynamics, insecticide application frequency, and even pollinator access. This dual impact introduces both benefits and trade-offs, especially in integrated pest management contexts.

Yield and production appeared as a major topic in 13 studies. This category focused on outcomes such as fruit yield per tree or hectare, fruit set percentage, and productivity efficiency based on trunk cross-sectional area (TCSA). The interaction between vegetative growth, environmental conditions under the nets, and productivity indicators was frequently addressed, showing how agronomic performance is intricately tied to the orchard's physical and physiological environment.

Physiological responses were addressed in nine studies, with emphasis on photosynthesis-related measurements like photosynthetic rate, stomata conductance, and transpiration rate. These studies provide insights into how hail nets influence plant metabolic activity and stress tolerance, particularly under high light or temperature conditions. The inclusion of variables like chlorophyll fluorescence and starch conversion also suggests a link between physiological status and fruit development.

The remaining categories, while less frequent, reveal additional important research dimensions. Coloration improvement (eight studies) focused on fruit aesthetics and marketability, particularly through measurements of color intensity, pigment composition, and maturation indices. Water use and irrigation (six studies) highlighted how netting affects evapotranspiration, water stress, and irrigation efficiency. Risk analysis and insurance (four studies) addressed economic impacts, including yield loss estimations and spatial modeling. Quality/economic losses (three studies), impact of insecticides/pesticides (three studies), pollination and biodiversity (three studies), and soil and leaf traits (two studies) were less explored, indicating potential gaps for future research.

Overall, the detailed breakdown of variables, grouped according to the objectives of each study, demonstrates the multifaceted influence of hail netting on apple production. While the majority of studies emphasize microclimate and fruit quality, the integration of physiological, ecological, and socioeconomic dimensions provides a broader understanding of how this protective technology impacts the entire orchard system. This synthesis also suggests that future studies could benefit from a more holistic approach bridging agronomic outcomes with environmental and economic sustainability.

Not all articles specified which net colors were used in their experiments. In some cases, more than one color was tested within the same study, depending on the research objectives or the availability of materials. Furthermore, the terminology used to describe

these structures varied across studies. While the present review focused on hail nets, several articles mentioned related or multifunctional structures, including photoselective nets, protective nets, or exclusion nets. While these nets have different applications, analyzing their physical characteristics and colors is important because these factors, in addition to hail protection, may affect the orchard microclimate, temperature regulation, pest incidence, and overall plant development.

Figure 5 displays the number of articles associated with each netting color. The most frequent colors were black and white, followed by red, blue, and green. Less common colors included gray, pearl, yellow, and crystal. Studies comparing multiple net colors aimed to assess their effects on variables like fruit quality, vegetative growth, and pest management.

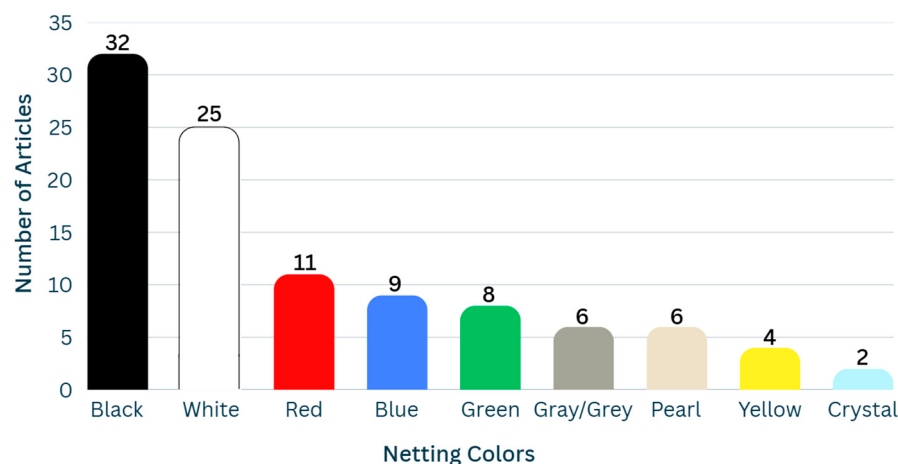


Figure 5. Number of articles according to the netting color used in apple orchards. The most frequently studied colors were black and white.

According to the studies analyzed, net color can affect apple quality, yield, maturation rate, and aroma volatile production, and can reduce wind velocity [20–22]. Black hail nets are widely adopted in apple orchards due to their proven efficiency in protecting trees from hail damage and mitigating excessive irradiance. However, their influence extends beyond physical protection. Microclimatic modifications induced by black nets include a 63% reduction in PAR, with the greatest effects occurring in the inner canopy [23]. This decreased light penetration delays apple maturation by up to one week compared with white nets [20], leading to reduced red blush development, reduced soluble solids content, and changes in titratable acidity, making fruits less attractive for fresh consumption [24,25]. In some cultivars, firmness and certain sensory attributes remain unaffected [24].

From a physiological perspective, black nets can enhance vegetative vigor, improve water and mineral status under high irradiance, and reduce oxidative damage, contributing to yield stability in hot, dry conditions [24,26]. Nevertheless, they may also accelerate the onset and peak intensity of diseases like GLS [27]. In terms of orchard management, chemical thinning programs under black nets, particularly combinations of benzyladenine, gibberellic acid, and ethephon, have been effective in controlling crop load, improving fruit size, and reducing manual labor [28]. Yield responses are cultivar-dependent, with some genotypes benefiting from increased fruit size and weight, while others show minimal or even negative effects [24–26].

Economically, black nets have higher annual costs compared with insurance-based hail protection, and, in some cases, reduced fruit coloration negatively impacted profitability [29]. These findings highlight the need to balance physical protection benefits with potential trade-offs in fruit quality and market value, as well as to explore strategies that optimize light management under black netting conditions.

White nets cause a lower reduction in PAR, allowing greater diffuse light penetration into the canopy [24,30]. This can promote earlier maturation, good yields, and balanced chemical parameters [25], but can also reduce skin coloration, increasing the proportion of fruits classified in the lowest color coverage categories [31]. White nets are effective in reducing bitter pit and sunburn and maintaining high yields, especially in high-density orchards [25,32]. It has also been observed that black and white nets produce bigger fruits compared to colors like yellow, blue or red [33]. Based on the reviewed studies, white nets consistently emerge as an effective option for maintaining high productivity and reducing disorders.

Red photosensitive nets significantly influenced both the physiological performance of apple trees and fruit quality. Compared to uncovered controls, red nets consistently reduced the incidence of bitter pit and sunburn [34], with the lowest percentage of damaged fruit recorded under red netting (0.96%) [35]. Instrumental measurements indicated that apples subjected to red netting had a higher mean fresh weight (217 g), larger cells with greater intercellular spaces, and a higher dry matter content than with other photosensitive net colors [36]. Red and blue nets showed the largest reductions in PAR (38.7–45.6%) [22], and the red net maintained titratable acidity and soluble solids at levels comparable to the control [37]. In terms of skin coloration, red nets generally outperformed white nets, with the latter tending to produce a higher share of low-color fruit (0–25% coverage) and a lower share in intermediate coverage classes (50–75%) [31].

Blue photosensitive nets had pronounced physiological and microclimatic effects in apple orchards, most evident under high light and temperature conditions [38]. They were the most effective at controlling sunburn, reduced red color development on the fruit surface, and consistently reduced bitter pit incidence in ‘Honeycrisp’ apples [34]. Soil temperatures were reduced more under blue and pearl nets than under red nets, and the volumetric soil water content increased [6]. However, a consistent increase in maximum air temperature of approximately 2% was observed, which may pose a risk in already hot environments [22]. Other fruit quality parameters were largely unaffected, making blue nets a valuable option for sunburn and bitter pit management [34].

Green nets also lead to PAR reduction [30]. Gray hail nets altered the orchard microclimate, reducing the susceptibility to radiation levels above the apple tree’s light saturation point and to hot, dry summer conditions [26]. They performed particularly well under cloudy conditions [26]. However, they were also associated with a significant reduction in tree growth and yield. This limited the effectiveness of fertilization management on replanted soils [39].

Pearl netting resulted in higher light interception as a consequence of stronger canopy development, increased vegetative growth, and larger leaf area [34]. Photosensitive pearl anti-hail nets have shown promise as an exclusion system capable of preventing attacks from multiple insect pests, enabling a substantial reduction in insecticide use and associated costs. Moreover, these nets did not adversely affect predator populations, fungal disease incidence, or fruit quality [40].

Yellow nets produced smaller fruit compared to black and white nets and had a lower proportion of apples in the desirable size class [33]. Although they provided moderate protection against fruit damage, they were associated with delayed ripening, as indicated by changes in titratable acidity and soluble solids content, and showed lower performance in yield and quality parameters compared to white and red nets [35,37]. Crystal nets represented a valuable option for ‘Eva’ apple trees, supporting both high fruit quality and high yields in commercial orchards [25].

Beyond the effects of different net colors, the review also considered the study area as an inclusion criterion. As a result, 25 countries were identified as having published studies

involving hail nets in apple orchards at some location within their territories. These study areas covered a variety of contexts, including orchards at experimental stations, research institutions, and commercial production sites. This approach allowed for the inclusion of studies from diverse geographic, climatic, and agronomic conditions, reflecting the global interest in evaluating the effects of hail nets on apple cultivation.

Figure 6 presents the 25 countries in descending order by the number of articles identified. Among them, nine countries stood out as the most frequent study locations: Italy, Brazil, Germany, United States of America (USA), Slovenia, Croatia, Switzerland, Mexico, and Spain, respectively. In contrast, the remaining 16 countries were represented by only one or two articles each, suggesting more limited, but still relevant, research activity in those regions.

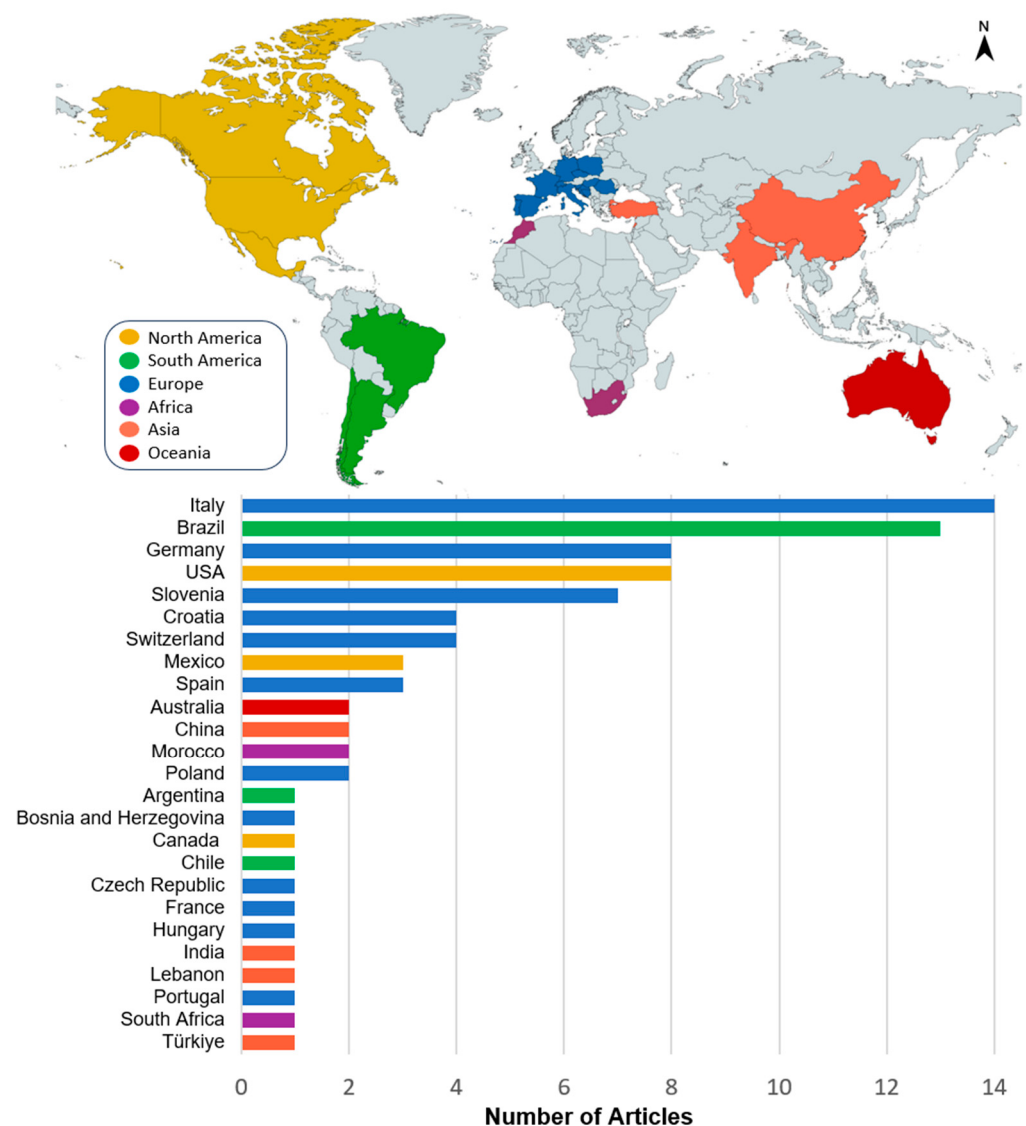


Figure 6. Countries identified as study areas in the reviewed articles. The figure displays all 25 countries in descending order by the number of articles. Each continent is represented by a different color, with North America in yellow, South America in green, Europe in blue, Africa in purple, Asia in orange, and Oceania in red.

The total number of articles exceeds 79 because some studies included more than one country. Europe leads with 47 mentions, followed by South America (15), North America (12), Asia (5), Africa (3), and Oceania (2). Despite the difference in quantity, it is important to highlight that apple production and the use of hail nets are present in all

continents, reinforcing the importance of applying modern techniques that optimize costs and benefit production worldwide [1,41].

Apple cultivation involves a wide range of varieties, each with specific agronomic traits, consumer preferences, and adaptability to different climatic conditions. These varieties may differ in fruit quality, harvest timing, susceptibility to pests, and their response to environmental factors such as temperature, light, and protective structures like hail nets. Understanding which varieties are most commonly studied provides insights into regional production priorities and the potential impact of hail netting technologies across different genotypes.

This review identified 49 apple varieties across the analyzed articles. Figure 7 presents the frequency of each variety in the studies, displaying only those cited in two or more articles and highlighting the predominance of Fuji, Gala, Royal Gala, Golden Delicious and Braeburn. Another 31 varieties appeared only once: Berner Rose, Borkh. cv. Cripps Pink, Borkh. cv. Honeycrisp, Braeburn Hillwell, Cameron Select® Honeycrisp, Cripps Pink, Early Gold, Eva, Fuji Mishima, Fuji Zhen, Gala Buckeye, Gala Mondial, Galaval, Galaxy Gala, Golden Reinders, Golden Smith, Granny Smith Challenger, Gravensteiner, Ladina, Mondial Gala, Nicogreen, Nicoter, Red Fuji, Red Prince, Redchief Delicious, Reinette, Šampion, Starking Delicious, Starkrimson, Story and Yanfu No. 8.

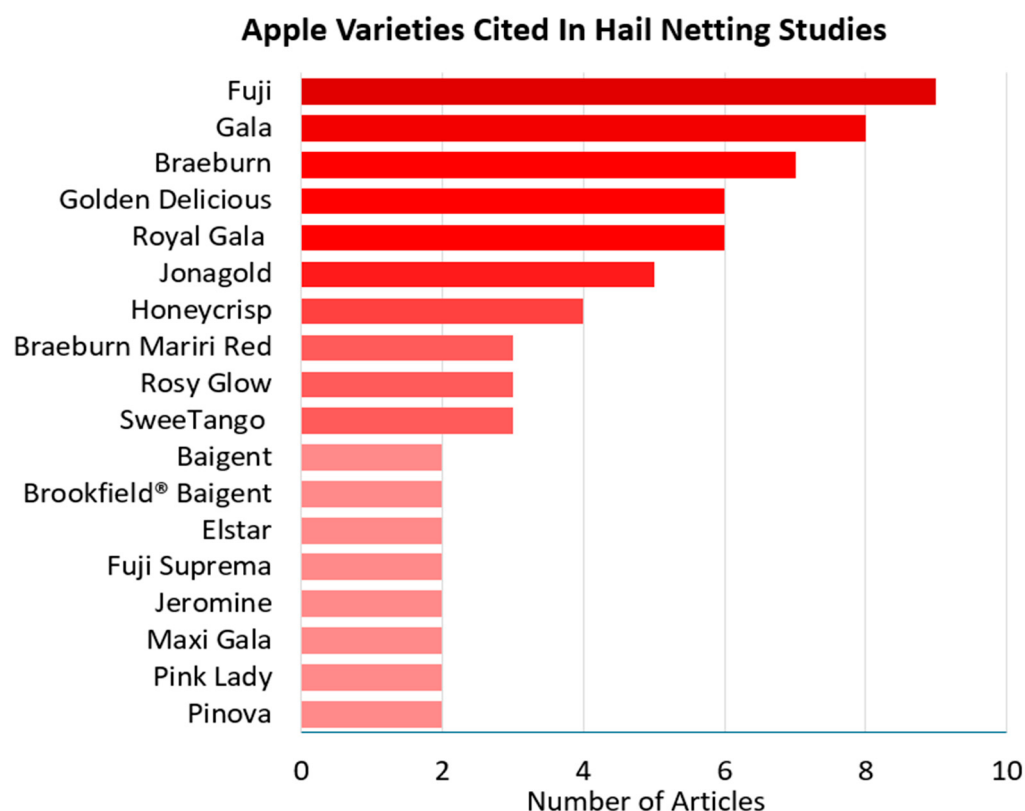


Figure 7. Frequency of apple varieties studied under hail netting systems. The horizontal bar chart shows the number of articles analyzing each variety, ranked from most to least frequent. The color gradient from dark red (top) to light red (bottom) reflects the decreasing number of studies per variety. Fuji, Gala, and Royal Gala emerged as the most frequently studied varieties.

Beyond identifying the most studied apple varieties, it is also important to examine the geographic distribution of research on these cultivars. Different countries may prioritize specific apple varieties due to factors like climate, biological factors, water availability, soil conditions, and management practices, underscoring the importance of studying and applying appropriate techniques across different countries [42]. Table 2 presents the distribution of the ten most frequently studied apple varieties across the countries included

in this review. This helps illustrate which countries contribute most to research on key cultivars such as Fuji, Gala, and Royal Gala, and may also reflect regional specialization or export potential. It is important to note that Table 2 refers to the countries associated with the ten varieties most frequently reported in Figure 7, rather than the varieties with the widest geographic distribution.

Table 2. Distribution of the ten most frequently studied apple varieties by country.

Apple	Countries
Fuji	Brazil, Germany, Italy, Lebanon, Slovenia
Gala	Brazil, Germany, Morocco, Switzerland
Braeburn	Croatia, Germany, Italy
Golden Delicious	Italy, Czech Republic, Mexico, Morocco, Portugal, Switzerland
Royal Gala	Australia, Brazil, Morocco
Jonagold	Germany, Lebanon
Honeycrisp	Canada, USA
Braeburn Mariri Red	Germany, Slovenia
Rosy Glow	Italy, South Africa
SweeTango	USA

‘Fuji’ emerges as the most widely investigated variety, with research conducted in five countries across both hemispheres (Brazil, Germany, Italy, Lebanon, and Slovenia). This widespread interest reflects Fuji’s global cultivation and commercial relevance. Similarly, ‘Golden Delicious’ shows a broad distribution, having been studied in six countries, mainly in Europe and North Africa, underscoring its importance under varied climatic and cultivation conditions.

Varieties such as ‘Gala’ and ‘Royal Gala’ also receive significant attention, particularly in countries like Brazil and Morocco, suggesting their adaptability and economic value in warmer climates. In contrast, some cultivars like ‘Honeycrisp’, ‘SweeTango’, and ‘Rosy Glow’ appear more regionally focused, with studies limited to only one or two countries. These patterns may be influenced by local market preferences, breeding programs, and export potential.

The recurrence of certain countries, especially Brazil, Germany, Italy, and Morocco, across multiple cultivars reflects a strong research presence and interest in apple production under diverse agronomic and climatic conditions. This distribution underscores not only the global relevance of apple production but also the strategic role of cultivar selection in studies addressing netting systems, fruit quality, pest control, and climate-related adaptations.

According to Figure 4, most of the reviewed articles (42 studies) were published between 2020 and 2025. Reflecting this recent growth, the most up-to-date research suggestions include topics such as pests, climate, plant physiology, and fruit quality, among others. Research gaps in pests studies persist, notably in understanding the ecological effects of hail nets, including potential changes in pest behavior, adaptation under high pest pressure, and risks to natural enemies and parasitoids. Greater attention is also needed for integrated practices, such as flower strips, reduced agrochemical input, and adjusted mowing strategies, which can enhance pollinator activity and improve crop yield. Taken together, these findings indicate that while netting reduces pest damage, its long-term sustainability depends on balancing productivity with ecological trade-offs [43–45].

From a management and adoption perspective, future research should explore the development of decision support models integrating both financial costs and benefits to guide long-term investments in hail nets. It is also necessary to assess how organic management practices interact with netting systems, particularly considering certification requirements and potential changes in production costs. Overall, the adoption of hail nets will likely depend on balancing economic viability with production sustainability [21,46].

Future studies should also address plant physiology and fruit quality under netting systems. Suggested approaches include evaluating strategies to mitigate reductions in red color development, such as adjusting net color, partially retracting nets, or applying reflective fabrics; investigating water status indicators, such as dry matter content, to complement plant water potential measurements; and assessing the effects of anti-hail nets on antioxidant activity and phenolic metabolism in apples treated with aminoethoxyvinylglycine (AVG). These efforts aim to link netting effects to both physiological processes and fruit quality attributes [15,34,47].

Future research should also focus on management practices in netted orchards. Priorities include the continuation of long-term trials to monitor vegetative vigor and the effects of different mesh sizes, the expansion of pesticide exposure studies to cover regular workdays for a more accurate assessment of occupational health risks, and the investigation of both light distribution within the canopy and the potential release of microplastics from netting materials into the soil. Thus, future research should not only aim to optimize productivity, but also to ensure environmental and worker safety [25,48,49].

Climate and light-related interactions also bring opportunities for future research. Suggested directions include testing the added value of combining netting with evaporative cooling under changing climate scenarios, investigating whether the spectral properties of nets influence soil temperature, evaluating the use of white or pearl exclusion nets in combination with rain shelters and extending these trials to other fruit crops, and continuing to assess how the quality of the visible light spectrum affects the accumulation of bioactive compounds. These suggestions reflect the need for integrated, climate-adaptive solutions that consider both environmental conditions and fruit quality [50–53].

Finally, perspectives on digital agriculture and monitoring are also emerging, as highlighted in [54]. Future research should explore how remote sensing, machine learning, and geoprocessing can be applied to orchard mapping and monitoring under netting systems, supporting the expansion of apple coverage assessments in Brazil and beyond. These initiatives suggest that research should go beyond physiological and ecological aspects of netting to also integrate technological tools that enable large-scale monitoring and management.

3.2. Regional Focus: Study in Vacaria (Brazil)

Vacaria, located in the northeastern region of Rio Grande do Sul, Brazil, is one of the country's main apple-producing areas [14]. With an estimated population of 64,197 inhabitants, the municipality stands out for its strong agricultural base and favorable climate for temperate fruit cultivation [55]. Vacaria experiences a highland subtropical climate (temperate oceanic climate—Cfb according to the Köppen classification), characterized by cold winters, mild summers, and well-distributed rainfall throughout the year [56]. These climatic conditions are ideal for growing apple cultivars such as Gala and Fuji, which require chilling periods to ensure proper dormancy breaking and optimal fruit development.

Apple farming is one of the economic pillars of the region, placing Vacaria among the leading apple production hubs in Brazil. The adoption of agricultural technologies, such as hail netting systems, has become increasingly common in the area, especially in response to extreme weather events like frost and hailstorms that threaten orchards [15]. Moreover, Vacaria hosts research centers that reinforce its strategic role in the development of innovative solutions for digital agriculture and commercial orchard management.

Figure 8 shows the location of Vacaria, along with examples of field photos collected in March 2025 using the Agrotag app [57]. During this fieldwork, a total of 105 apple-related points were collected throughout the municipality. Each point included georeferenced

coordinates, a photo of the orchard, and specific information regarding the presence or absence of hail netting.

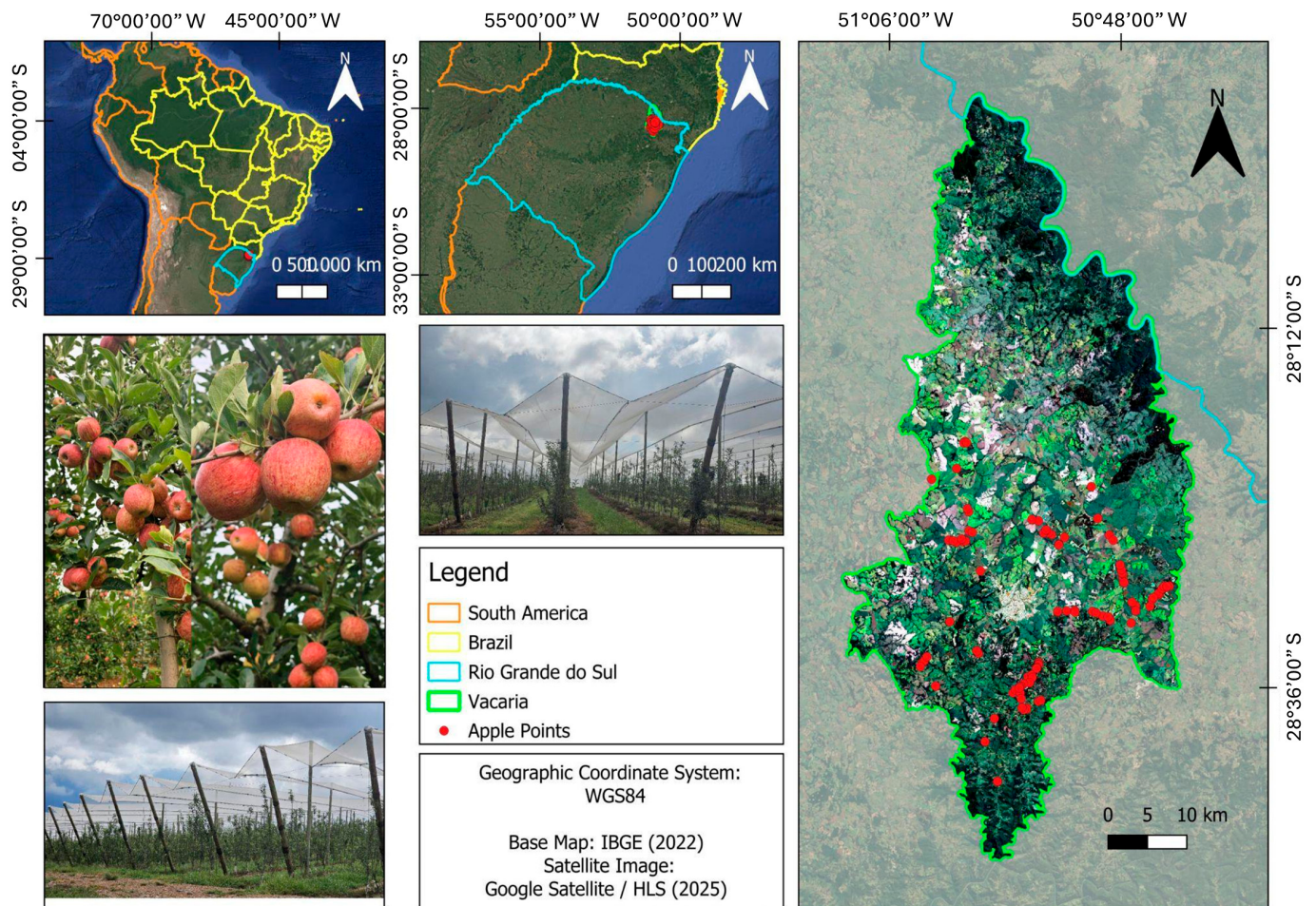


Figure 8. Location of Vacaria, Rio Grande do Sul. The figure shows examples of field photos taken in March 2025, showing orchards with white hail netting and Fuji apple cultivation. Additionally, the map shows the 105 apple points collected during the fieldwork.

Vacaria stood out in the systematic review, with five studies dedicated to the use of hail nets in apple orchards. Table 3 summarizes the five articles conducted in Vacaria.

Figure 8 and Table 3 highlight the strong potential of Vacaria as a key study area for RS and AI applications in fruit production. The region presents a high concentration of commercial apple orchards, including both Fuji and Gala cultivars, distributed across diverse planting systems. The municipality contains a substantial number of areas with and without protective netting, enabling detailed comparative analyses under varied orchard conditions.

This spatial diversity allows researchers to design and validate robust methodologies for fruit detection, classification, yield estimation, and crop monitoring using RS and AI tools. Moreover, Vacaria's inclusion in the Semear Digital Project further enhances its relevance by providing access to high-quality field data, remote sensing products, and collaborative research frameworks. This integration supports the development of innovative technologies that not only benefit local producers but also contribute to broader advancements in Brazilian agriculture and global digital farming practices. In this sense, the local analysis complements the worldwide review, with Vacaria serving as an example of how global knowledge can be applied in a strategic apple-producing hub. Nevertheless,

the information and perspectives discussed can be applied to any country, not exclusively to Brazil.

Table 3. Studies from Vacaria addressing anti-hail nets in apple orchards.

Reference	Focus	Data	Results
Bosco et al., 2015 [58]	Evaluated the effects of anti-hail nets on the physical, chemical, and sensory attributes of apples grown in southern Brazil.	Black hail net; PAR measurements; physical, chemical, and sensory fruit analyses (2008–2011)	Anti-hail net reduced PAR by 32% and altered R/FR (red/far-red) ratio; slightly delayed fruit ripening without affecting the quality of ‘Royal Gala’ and ‘Fuji Suprema’ apples.
Bosco et al., 2018 [59]	Characterized the microclimate and productivity of apple orchards under hail nets, providing numeric parameters to support orchard management and crop modeling.	PAR, temperature, humidity, wind, and rainfall were continuously measured; yield was assessed by fruit number and weight per plant.	Hail nets reduced PAR by 32.8% and wind speed by 30%, without affecting air temperature, humidity, or rainfall. Apple yield tended to be higher under the nets, especially when hail events occurred.
Soethe et al., 2022 [15]	Evaluated the effects of aminoethoxyvinylglycine (single or split dose), with or without ethephon, on fruit quality, antioxidant activity, and phenolic content of ‘Baigent’ apples grown under black hail nets after controlled atmosphere storage.	Apples were stored for 8 months in controlled atmosphere (CA) conditions. The study assessed fruit quality parameters including firmness, color, ethylene and CO ₂ production, total antioxidant activity, phenolic compound content, and physicochemical attributes. Statistical analysis used a randomized block design with Tukey’s test and Pearson correlation. The experiment included control and five treatments combining different doses of AVG and ethephon applied at various pre-harvest intervals. Fruits were harvested at the commercial maturity date and again 14 days later.	AVG reduced ethylene, yellowing, and cracking; maintained firmness and acidity. Combined with ethephon, it increased decay. Reduced skin phenolics and antioxidants; no effect on flesh.
Soethe et al., 2021 [60]	Evaluated the effect of pre-harvest spraying with AVG and ethephon on fruit maturation of ‘Baigent’ apple trees grown under black anti-hail nets.	Meta-analysis of 26 peer-reviewed articles on apple orchards across 17 locations, using Main Effects Meta Principal Components Analysis (ME Meta-PCA) to assess effects of netting, cultivar, climate, and planting density.	AVG treatments delayed fruit yellowing and firmness loss, indicating slower maturation, while ethephon accelerated these processes. A single 125 mg L ^{−1} AVG dose reduced red coloration, but split doses did not affect color, regardless of ethephon use or harvest timing. Netting had minimal effect on yield but reduced red color and sweetness (TSS). Fruit firmness and acidity were slightly affected. Gala and Jonagold were the most stable; Pinova was the least suitable. Late cultivars like Braeburn and Cripps Pink showed earlier ripening under netting.

3.3. Challenges, Future Perspectives and Technological Opportunities

The results of the PRISMA review revealed a significant gap in the literature concerning the use of AI and RS for the study of hail netting in apple orchards. None of the reviewed articles employed AI algorithms to analyze or monitor the use and effects of hail nets, and only one study incorporated RS technologies, specifically using Sentinel-2 imagery [54]. No applications involving other sensing datatypes, such as hyperspectral imagery, LiDAR point clouds, or in situ sensor networks, were identified. These approaches could provide valuable insights into canopy structure, microclimatic variability, and the mechanical performance of hail nets, representing promising directions for future research. This represents an opportunity for the integration of digital agriculture tools in this research domain [54].

In the context of Vacaria, a prominent apple-producing region in southern Brazil with susceptibility to hail events, these technological tools could be especially valuable. The integration of AI and RS could support the quantification of hail net coverage over time, the identification of microclimatic variations under different net types, and the assessment of potential correlations with yield and fruit quality. Such innovations would offer practical benefits for regional producers, aiding in risk mitigation and decision-making.

These technological approaches also align with the goals of the Semear Digital Project, which promotes the adoption of digital agriculture among small and medium-sized farms. By incorporating AI and RS into studies on hail netting, Vacaria could serve as a model for the development of scalable solutions applicable to other apple-producing regions in Brazil and internationally. Applications may include monitoring canopy temperature via thermal imagery, evaluating vegetation indices under different net types using multispectral sensors, or implementing automated classification of orchards with and without netting. These strategies not only improve research outcomes but also empower growers with accessible tools for more efficient orchard management.

Furuya et al. (2024) [14] reviewed studies that combined remote sensing and artificial intelligence for fruit growing. One of the authors' analyses included articles that combined these techniques for apples. Figure 9 shows the gap in the application of RS and AI to apples.

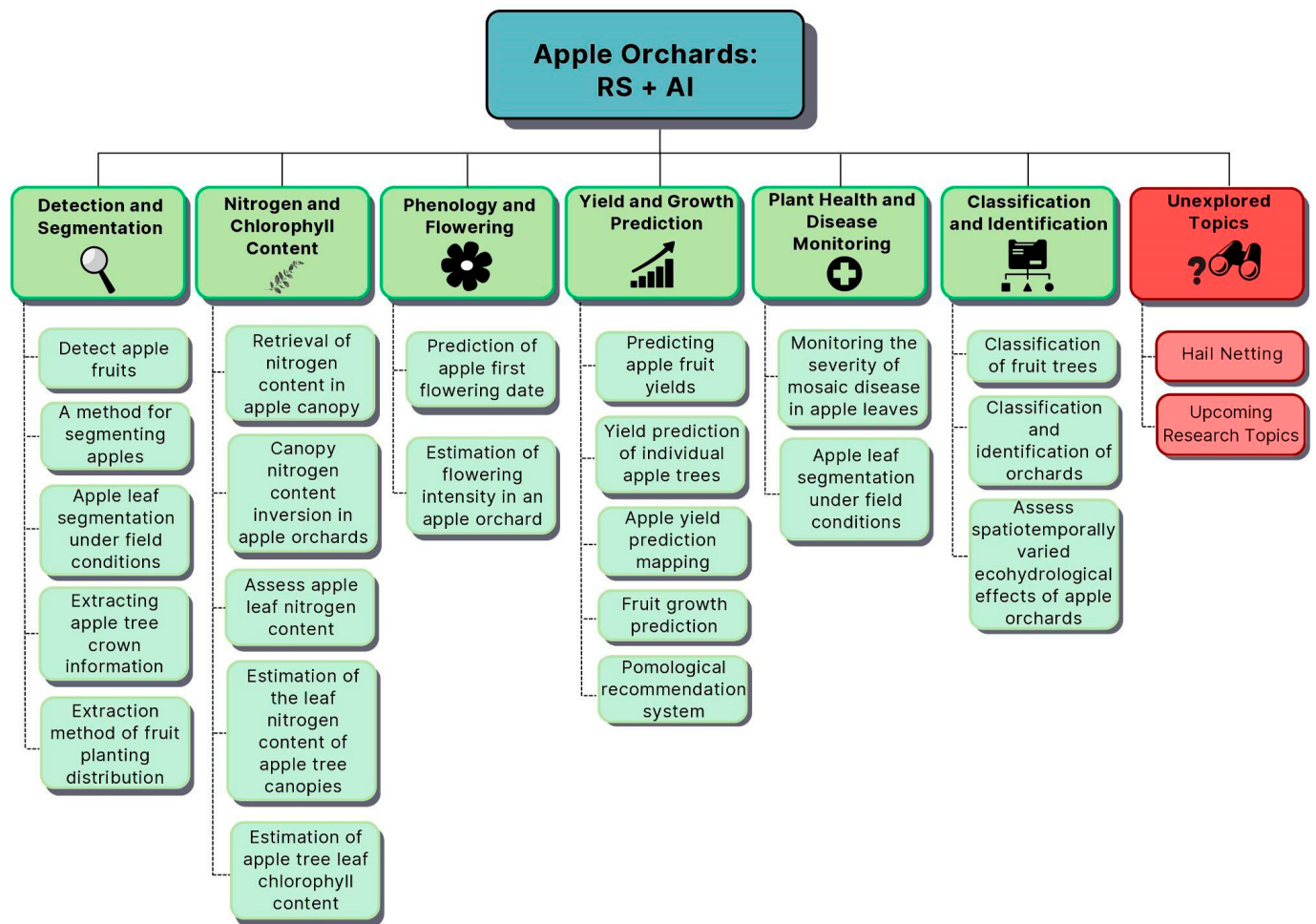


Figure 9. Applications of RS and AI in apple orchards, grouped into six main themes: Detection and Segmentation, Nitrogen and Chlorophyll Estimation, Phenology and Flowering, Yield and Growth Prediction, Plant Health and Disease Monitoring, and Classification and Identification (Furuya et al., 2024 [14]). The theme “Hail Netting” is highlighted in a different color with a question mark to emphasize the research gap identified in this review.

RS offers powerful tools to evaluate the impacts of hail netting in apple orchards at different scales. The use of multispectral and hyperspectral data with varying spatial resolutions, ranging from medium-resolution imagery such as Landsat (30 m) to higher-resolution products like Sentinel-2 (10–20 m) and Harmonized Landsat–Sentinel (HLS) datasets, can enable temporal monitoring of canopy development, physiological responses, and spectral signatures under different netting conditions [62,63]. In addition, very high-resolution imagery from commercial satellites such as PlanetScope (3–5 m) [64] enable detailed orchard-level analysis, capturing microclimatic effects caused by nets on vigor, light interception, and fruit quality. The combination of these sensors provides an unprecedented capacity for long-term and large-scale monitoring of orchards under protective structures.

Machine learning algorithms are increasingly relevant for extracting information from remote sensing data in netted orchards. Techniques such as Random Forest (RF) have proven effective in classifying vegetation cover, climate data and identifying management practices [65–67], offering robust models for mapping the extent of hail net adoption. More-

over, regression-based ML models can support the estimation of biophysical parameters (e.g., leaf area index, chlorophyll content, canopy temperature) that are potentially altered by hail nets. By integrating multisensor datasets, these approaches allow the identification of subtle spectral and structural differences between covered and uncovered orchards.

Deep learning approaches, particularly Convolutional Neural Networks (CNNs), provide advanced capabilities for image segmentation and feature extraction at the orchard level [68,69]. CNN-based architectures may detect orchard patterns, quantify the area covered by nets, and evaluate crop performance under protective structures with high accuracy. When applied to time series data, deep learning models can further track phenological changes and growth dynamics in orchards, revealing long-term impacts of hail netting. These methods open perspectives not only for monitoring netting adoption but also for predicting yield and fruit quality under different management and environmental conditions.

The integration of RS with ML and DL offers a robust framework for studying hail netting in apple orchards. By combining multi-resolution satellite imagery with advanced algorithms, it becomes possible to conduct both large-scale mapping and detailed orchard-level assessments, complementing field studies with continuous and spatially explicit information. This integration can enhance the understanding of how hail nets influence the micro- and macroclimate, plant physiology, and fruit quality while also supporting the development of decision-support systems for growers. Furthermore, coupling historical climate data, satellite observations, and predictive models enables the identification of areas most vulnerable to extreme weather, the generation of early warning systems, and even the characterization of fruit attributes. Together, these approaches contribute not only to improved orchard resilience and the effective use of protective systems such as hail nets, but also to broaden the advancement of digital agriculture and smart farming [14,70–72].

The implementation of these technologies in the study and monitoring of hail netting faces several practical and structural challenges. First, the acquisition of high-resolution satellite imagery and hyperspectral sensors still involves high costs, which limit access for small- and medium-sized producers [73]. In addition, hyperspectral sensors suffer from limited temporal resolution, which hinders the effective monitoring of rapid changes on the Earth's surface [74]. The application of machine learning and deep learning algorithms also requires robust and well-structured databases, which are often unavailable in producing regions such as Vacaria [14]. Another obstacle is the need for adequate digital infrastructure, rural connectivity, processing capacity, and cloud storage—which remains limited in much of Brazil's agricultural territory [75,76]. Added to this is the lack of technical training among farmers and local technicians, which restricts the adoption of advanced digital tools, as well as the absence of public policies and specific incentives aimed at integrating these technologies into fruit growing [77]. These combined factors explain the gap observed in the literature and reinforce the need for collaborative strategies among research centers, the productive sector, and the government to enable the effective use of AI and RS in this context.

4. Conclusions

This study provides a comprehensive overview of research on the use of hail netting in apple orchards by integrating a systematic PRISMA-based literature review, a regional analysis focused on the city of Vacaria, and a forward-looking discussion on digital agriculture applications. The first stage identified the main scientific trends and knowledge gaps, highlighting a strong emphasis on fruit quality, microclimatic effects, and pest management while revealing a significant lack of studies employing artificial intelligence and remote sensing technologies. The second stage demonstrated that Vacaria, a major apple-producing

region in Brazil, has already investigated key aspects such as fruit protection, netting colors, and climate conditions, providing a solid foundation for further exploration.

Finally, the third stage addressed possible future directions that align with the goals of the Semear Digital Project and the growing need for technological innovation in digital agriculture. The integration of AI and RS could enhance the monitoring and management of hail nets by enabling automatic identification of net coverage, spatial quantification of protected areas, and the analysis of biophysical and climatic parameters under different netting conditions. These tools offer scalable and replicable solutions not only for Vacaria but also for other apple-producing regions facing similar environmental challenges.

By combining bibliometric analysis, regional insight, and technological perspectives, this study contributes to a better understanding of the current landscape and future potential of hail netting research in apple orchards. It encourages researchers, policymakers, and producers to adopt digital strategies that promote productivity, resilience, and sustainability in fruit production systems.

While this study focused on perspectives related to RS and AI within the context of digital agriculture, we also highlight that future research should explore more detailed microclimatic monitoring under different net colors and densities, for example, through stratified IoT sensor networks coupled with RS data. In addition, future reviews may broaden the scope to address pest management, socioeconomic impacts, public policy, and capacity-building for producers and rural extension, complementing the technological dimension and contributing to a more comprehensive understanding of hail netting in apple orchards.

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Abbreviations

AI	Artificial intelligence
AVG	aminoethoxyvinylglycine
CA	Controlled atmosphere
CCD	Center for Development in Digital Agriculture
Cfb	Temperate oceanic climate (Köppen climate classification)
CNNs	Convolutional Neural Networks
DAT	Agrotechnological Districts
DL	Deep Learning
GLS	Glomerella Leaf Spot
ME Meta-PCA	Main Effects Meta Principal Components Analysis
ML	Machine Learning
PAR	Photosynthetically active radiation

PRI	Photochemical Reflectance Index
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RF	Random Forest
R/FR	red/far-red
RS	Remote Sensing
TCSA	Trunk Cross-Sectional Area
TSS	Total Soluble Solids
QY	Quantum Yield
WoS	Web of Science

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