RESEARCH ARTICLE

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SafeWax: A Bio-Inspired Multifunctional Coating for Sustainable Crop Protection

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Modern agriculture faces numerous challenges, including the rise of fungal diseases and the effects of climate change. Traditional reliance on chemical pesticides poses environmental hazards, such as the emergence of resistant fungal strains. SafeWax, a biodegradable and multifunctional coating, provides a sustainable alternative by emulating natural plant wax cuticles. Its superhydrophobic surface prevents fungal adhesion and colonization, while also protecting crops from ultraviolet (UV) radiation and low humidity. Additionally, the self-cleaning properties of SafeWax coatings enhance water collection, promoting robust plant growth and productivity. Initial studies demonstrate the ability of SafeWax to reduce fungal infections and boost the resilience of crops like grapevines and tomatoes. This paper aims to introduce the SafeWax technology, explain its mechanisms, present preliminary results from lab and greenhouse trials, and discuss its potential to lower the demand for conventional pesticides in alignment with the European Green Deal, which targets a 50% reduction in pesticide use by 2030.

1. Introduction

Agriculture is under growing pressure to meet the demands of an increasing global population while simultaneously reducing its environmental footprint. The traditional reliance on chemical fungicides to combat crop diseases and their overly use has led to numerous negative consequences. For example, fungicides are often washed off the plant and may cause soil degradation, harm aquatic ecosystems, and/or reduce biodiversity.[1] Additionally, the widespread use of these chemicals has accelerated the development of fungicide-resistant strains of pathogens, making it increasingly difficult to control fungal diseases in crops.[2] This has resulted in a cycle where higher doses and/or new types of pesticides are

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required to achieve the same level of protection. These issues, and concurrent adverse effects of climate change, have established a critical need for more sustainable and eco-friendlier technologies for crop protection in agriculture, as stipulated by the European Green Deal.[3] In fact, one of the targets of the so-called "Farm to Fork"[4] strategy is a 50% reduction in the use and risk of chemical pesticides by 2030. To achieve this ambitious goal, innovative pesticide-free crop protection methods with high effectivity and low environmental footprint need to be developed and adopted, as reflected in the priorities discussed at the EU Agri-Food Days 2024.[5]

Viticulture is particularly vulnerable to the complex impacts of climate change, especially in regions like the Mediterranean, where accumulation of CO_2 and other greenhouse gases in the atmosphere is driving a significant increase in average temperature. Projections indicate that these effects will intensify over the next decade and pose major challenges to grape production and wine quality.[6] Elevated temperatures will directly affect viticulture through soil overheating, changes in plant fertility, and physiological alterations in grapevines. Indirect negative consequences are expected from pathogen epidemiology and, in particular, an increase in the severity of crop diseases like powdery and downy mildew,[7] which will place additional stress on vineyards and require adaptive disease management strategies.[8] One critical example is *Plasmopara viticola* (*P. viticola*), the oomycete responsible for grapevine downy mildew. This pathogen is particularly sensitive to environmental conditions and is expected to thrive at the projected higher temperatures and the accompanying increased relative humidity.[9] This, together with earlier vegetative restart in grapevines, will likely lead to enhanced susceptibility of the vines to fungal infection. Furthermore, warmer conditions may trigger the premature exit of downy mildew oospores from quiescence and thus extend the window for potential pathogen infection. Studies since 2000 have shown that earlier oospore germination directly translates into longer periods of infection, favoring the spread of diseases like downy mildew and rendering effective crop protection increasingly challenging.[10] In parallel, the increase in temperature and evaporation rates will negatively impact grapevine physiology, potentially forcing the grape-growing regions to shift further north or to higher altitudes in search of more favorable conditions.

The epidemiology of *Erysiphe necator* (*E. necator*), the fungal pathogen responsible for grapevine powdery mildew, is also influenced by temperature and rainfall patterns. However, unlike *P. viticola*, *E. necator* is highly adaptable to a wide range of thermal conditions, thriving in both hot and cooler climates.[11] This pathogen has demonstrated the ability to shorten its latency period at higher temperatures and enhance asexual sporulation, resulting in increased disease severity.[12] Overall, rising temperatures and extended growing seasons are expected to drive the evolution of both *P. viticola* and *E. necator*, enabling these pathogens to survive and proliferate under the conditions of a changing climate. At the same time, authorities are striving to restrict the volumes and chemical spectrum of conventional pesticides. As a result, viticulture in geographical regions like the Mediterranean may face growing pathogen pressure and increasingly limited options for disease control. This challenging combination of changes highlights the urgent need for alternative crop protection strategies that do not rely on conventional pesticides or at least lower the necessary pesticide dosage while maintaining (or even improving) effectivity and meeting sustainability criteria. SafeWax is one such alternative technology aiming to reduce or even fully prevent fungal infections in crop plants by surface modification with biobased and biodegradable components while avoiding or minimizing the use of pesticides. Based on its passive (i.e., non-chemical mode of action), we envision that SafeWax could enable a 50–70% reduction in chemical fungicide use, particularly in crops vulnerable to fungal infections. Depending on the crop type and disease severity, this new technology may be applied either as a standalone protective coating or in combination with reduced fungicide inputs, offering a flexible approach to lowering the demand for conventional pesticides while maintaining crop health and productivity. While initially validated on grapevines, SafeWax is intended to show broader applicability with potential use across other economically important crops (e.g., tomato and wheat) that face similar challenges related to climate stress and fungal diseases. In this conceptual paper, we introduce the basic idea behind this green technology, elucidate the mode of action, present preliminary feasibility tests on selected model crops, and devise future directions to further develop SafeWax into a sustainable solution that may help address the growing challenges faced by modern agriculture.

2. Results and Discussion

2.1. SafeWax Concept – Learning from Nature's Defense Mechanisms

Plants have evolved highly efficient defense mechanisms to protect themselves against a variety of threats such as pathogens, insects, and environmental stressors. A key component of this defense is the cuticle, a waxy layer that covers the surface of leaves, stems, and fruits and often exhibits hydrophobic characteristics.[13] This layer serves as a multifunctional barrier that minimizes water loss, regulates gas exchange, reduces surface temperature, and provides protection against harmful radiation.[14] On some plant surfaces, like the well-known Lotus leaf, the cuticle displays a hierarchical structure, and is covered by wax nanocrystals, which together generate superhydrophobic properties.[13a,15] When water droplets land on such surfaces, they form spherical beads that effortlessly roll off and thereby carry away pathogens like fungal spores or debris.[16] Superhydrophobicity has also shown to prevent the adhesion and entry of pathogens, because germination of these pathogens is limited by access to water.[16,17] Various bio-inspired synthetic approaches have successfully replicated the functional features of plant surfaces leading to the fabrication of synthetic surfaces with superhydrophobic properties accompanied by antimicrobial characteristics.[18] Unfortunately, there are various crop plants that lack a natural waxy barrier and/or the superhydrophobic features required for self-cleaning and anti-adhesion against pathogens. To protect such crops, we have developed a synthetic coating named "SafeWax", which draws inspiration from Nature and replicates the protective functions of superhydrophobic plant cuticles. Much like its natural counterparts, this innovative coating forms a superhydrophobic barrier on crop surfaces and thereby renders them self-cleaning. This prevents fungal spores from adhering and colonization, and eliminates surface

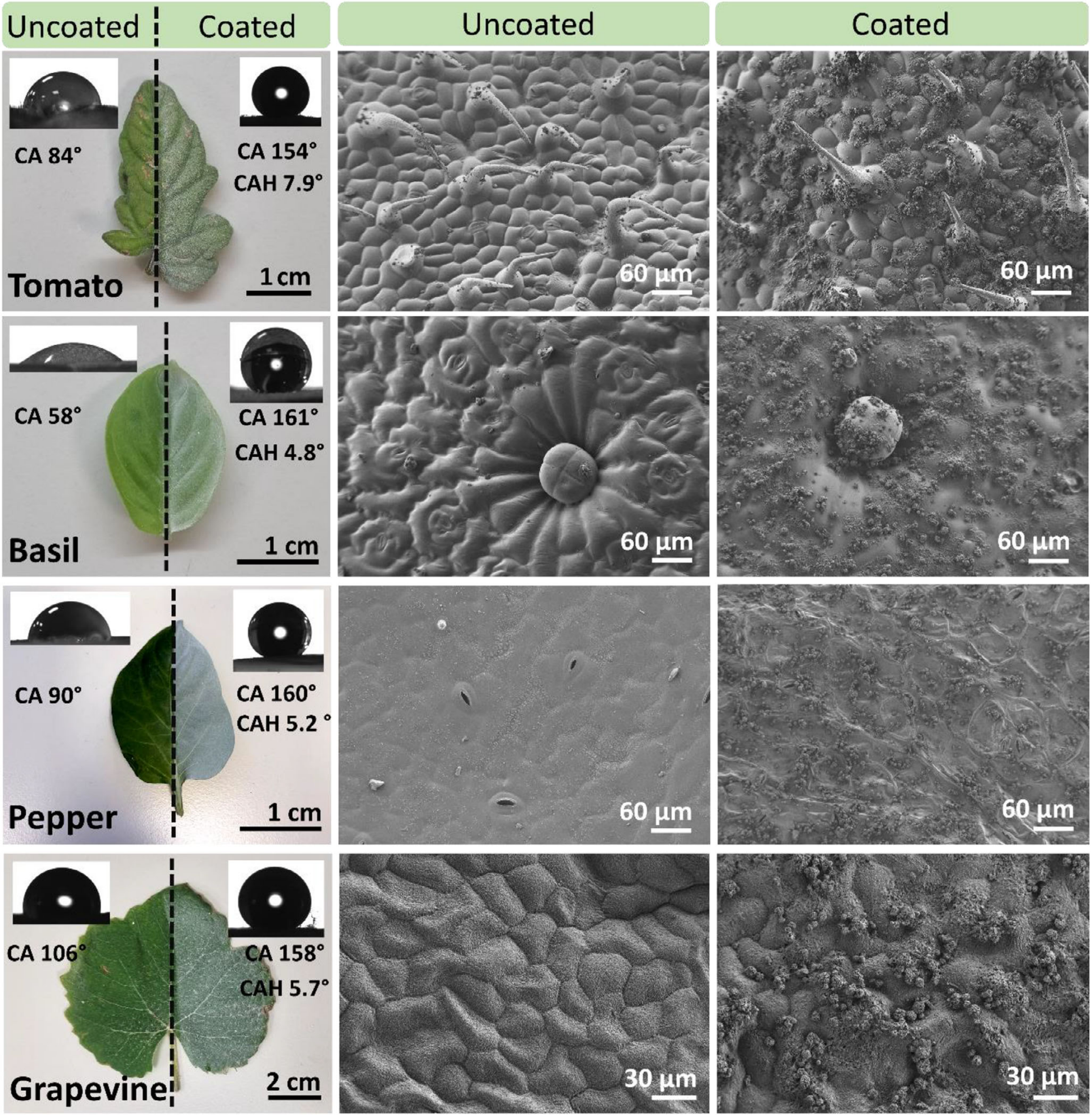


Figure 1. Demonstration of the SafeWax coating on plant leaf surfaces. Left column – photographs of leaves from four different plants and their water CAs and CAH before and after coating. Middle and right columns – HR-SEM images of the leaves before and after coating, respectively.

accumulation of water required for the germination of pathogens. In addition, SafeWax may facilitate improved crop resilience to abiotic stressors, such as dehydration as a consequence of extreme temperatures and drought, or photochemical damage due to harmful UV radiation. The coating consists of biobased saturated fatty acids such as stearic or palmitic acid as the core components. A SafeWax formulation can be prepared simply by dissolving a commercially available saturated long-chain fatty acid in a volatile organic solvent, such as diethyl ether (DEE). The resulting clear and homogeneous solution is then applied onto plant surfaces via a facile spraying technique using a commercially available spray gun. The desired superhydrophobic coating forms spontaneously by the rapid crystallization of the fatty acids upon solvent evaporation. **Figure 1** shows photographs and high-resolution scanning electron microscopy (HR-SEM) images taken from leaves of four different types of plants (tomato, basil, pepper, and grapevine) before and after treatment with stearic acid-based SafeWax formulation. The coating becomes evident as a visible white film, while microscopically numerous aggregates of fatty acid crystals are found to be scattered across the leaf surfaces. These hydrophobic fractal structures repel water effectively and result in contact angles (CA) as high as 150°–160° and a typical contact angle hysteresis (CAH) of less than 8° (see insets in Figure 1).

Thus, our approach mimics the waxy cuticles found on plant surfaces that serve as the first line of defense against pathogens and environmental stressors. In the following, we describe the concept of the SafeWax technology in more detail and highlight its prospective role in transforming crop protection toward more sustainable practices by offering an environmentally friendly alternative to conventional chemical fungicides.

2.2. SafeWax Development and Formulation

SafeWax is formulated using fatty acids derived from vegetable food waste, which ensures that the coating is both sustainable and cost-effective. Numerous studies show that abundant amounts of saturated fatty acids such as palmitic or stearic acid can be recovered from fruit and vegetable waste. By applying green extraction techniques based on eco-friendly solvents,[19] supercritical fluids,[20] or hydrolysis[20b,21] these fatty acids can be obtained from seeds, peels, bean shells and other food residues. Turning waste streams into new resources via eco-conscious ways not only promotes circular economy principles but also provides raw materials for novel bio-based sustainable products, such as SafeWax. Importantly, long-chain fatty acids are biodegradable.[22] Although their intermediate degradation products may cause short-term effects on microbial communities and nutrient availability, they usually do not cause significant long-term changes in pH levels of topsoil, and are potentially well-tolerated, specifically in non-acidic agricultural soils with moderate to high content of organic matter.[23] As SafeWax coatings consist exclusively of these bio-derived compounds, the technology is envisaged to support long-term soil health with minimal disruption to soil microbial communities, unlike conventional synthetic or heavy metal-based fungicides. Commercially available stearic and palmitic acids were selected for their unique ability to crystallize into stable wax structures on plant surfaces when sprayed from a rapidly evaporating solvent such as DEE, creating the desired superhydrophobic effect. The latter is achieved by the hierarchical roughness generated by the fatty acid crystals in combination with the intrinsic hydrophobic character of the aliphatic chains.[24] The SafeWax coating effectively adheres to the plant surface and maintains its effectiveness. Once applied, it forms a thin and semi-transparent layer on the surface of the plant (see Figure 1, left column), preserving its ability to grow and thrive while ensuring minimal impact on photosynthesis.

2.3. Mechanism of Action

SafeWax works through a structural mechanism and thereby offers a fundamentally different approach compared to the chemical modes of action employed by traditional fungicides. Instead of directly targeting pathogens with toxic compounds, SafeWax creates a physical barrier that protects plants from infection. When applied onto a plant surface, it forms a hierarchical structure of self-assembled wax crystals on the surface. This architecture is extremely repellent against water: in contact with a water droplet, a so-called Cassie–Baxter wetting state is established, in which air pockets are trapped between the superhydrophobic plant surface and the water droplet.[25] Consequently, the droplet cannot spread on the surface and readily rolls off even at low angles of inclination.

The superhydrophobic properties of the SafeWax coating protect the plant against fungal infections in two ways. First, the combination of micro-structured surface topography formed as a result of the spraying process and inherent low surface energy offered by fatty acids results in the formation of a crystalline superhydrophobic, self-cleaning coating that prevents fungal spores from adhering to the plant surface, which reduces the likelihood of infection via a passive and non-chemical mode of action. Second, many fungal pathogens require a thin and persistent layer of moisture on the surface to germinate and colonize,[26] which is effectively prevented as a result of the superhydrophobic properties and the decreased moisture retention time on the leaf surface provided by the SafeWax coating. For example, under early morning dew conditions, leaves coated with SafeWax remain dry while uncoated leaves retain dew, which creates a favorable moist environment for fungal growth. In addition to the benefits of superhydrophobicity, the SafeWax coating may impede fungal infections simply by posing a physical barrier through which spores must penetrate.[27]

Beyond its antifungal capabilities, SafeWax also protects plants against abiotic stressors and thus enhances crop resilience in challenging environments. By reducing water loss through transpiration, the coating supports crops in preserving moisture, thus improving their drought resilience. Furthermore, SafeWax may serve as a protective shield against UV radiation, which can cause cellular damage and reduce photosynthetic efficiency. Another distinctive feature of the coating is its ability to facilitate water collection: dew that condenses on coated plant leaves can roll off to the ground instead of remaining pinned on the leaf surface and evaporating back to the atmosphere. To the best of our knowledge, there is currently no existing commercial coating product that combines superhydrophobicity with the multifunctional protective capabilities offered by SafeWax. While formulation ingredients like silicone-based surfactants, film-forming agents, or adjuvants may enhance pesticide retention, spreading or uptake, they do not provide passive protection against pathogens. In this regard, SafeWax offers multiple benefits and may develop into a versatile and sustainable solution for agricultural use.

2.4. Preliminary Experimental Results

A series of laboratory trials were conducted to assess the compatibility of SafeWax coating application on plant surfaces and to evaluate its potential efficacy in protecting crops against fungal infections and environmental stressors, using plants that are known to be particularly susceptible to a range of fungal pathogens. In a first test, we applied SafeWax to a living bamboo plant to determine whether the coating could be effectively applied to the plant's leaves without hindering their growth or health. Key criteria were the adhesion of the coating to the plant surface, its

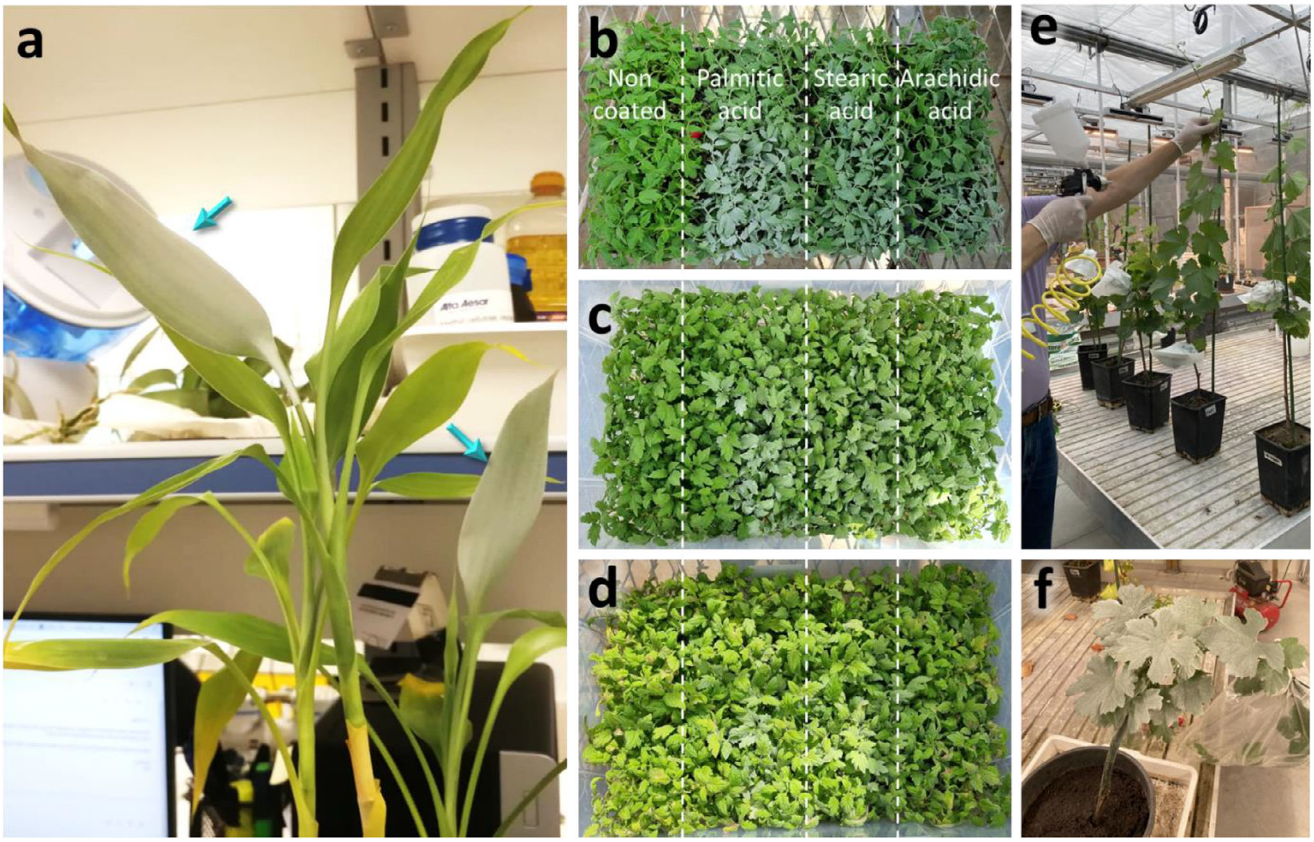


Figure 2. SafeWax application tests on living plants. a) A bamboo plant coated with stearic acid-based SafeWax in 2020, showing healthy growth for over a year. b–d) Tomato plants treated with SafeWax formulations based on palmitic, stearic, or arachidic acid, in comparison to an untreated control, after 0 (b), 11 (c), and 24 (d) days. e,f) Grapevine potted plants treated with stearic acid-based SafeWax and monitored under controlled greenhouse conditions for over 6 months.

ability to repel water, and its compatibility with the plant's physiological processes. The naturally hydrophobic bamboo leaves, with a water contact angle of 95°, became superhydrophobic after being coated with SafeWax, reaching CA values of around 150°. Accordingly, the coated leaf surfaces effectively repelled water and exhibited a clear roll-off behavior. Furthermore, the plant exhibited no signs of adverse effects or damage from the coating and continued to grow healthily for over a year, as demonstrated by **Figure** 2a. These early findings confirmed that SafeWax may render plant surfaces superhydrophobic without interfering with plant growth or its physiological processes, making it a promising candidate for broader agricultural applications.

Further compatibility tests were conducted on young tomato plants, which were spray-coated with SafeWax formulations based on palmitic, stearic, or arachidic acid using DEE as solvent. After 11 days in the greenhouse, no visible phytotoxic symptoms were observed on the coated plants (Figure 2b,c). Slight chlorosis was observed after 24 days for both untreated and coated plants that were located along the perimeter of the box (Figure 2d), most likely due to soil depletion or general plant dehydration, i.e., stressors that are unrelated to the coating. In another feasibility assessment, the potential of SafeWax was evaluated with potted grapevine plants that were maintained under greenhouse conditions (Figure 2e,f). Plants coated with a stearic acid-based formulation showed no signs of foliar damage and sustained growth over a period of six months, supporting the physiological compatibility of the coating under semi-controlled conditions. In the preliminary tests summarized in Figure 2, the SafeWax coatings remained stable on growing leaves without visible failure. However, it is important to note that newly emerging leaf surfaces will always require reapplication.

To further investigate and quantify the effect of the SafeWax coating on the photosynthetic efficiency, additional trials were conducted to assess key physiological parameters of the SafeWax-coated plants. Specifically, we evaluated the stomatal conductance (*gsw*) and transpiration rate (*E*) for pepper, tomato, and vine plants under controlled greenhouse conditions following the foliar application of SafeWax. Stomatal conductance quantifies the rate at which CO_2 enters and water vapor exits through the stomata, while the transpiration rate provides a measure of the water vapor loss from the leaf surface due to stomatal opening (which is a direct indicator of the plant's efficiency in the use of water). Both parameters are key physiological parameters to assess whether the wax layer formed by SafeWax affects plant water loss and transpiration activity. Pepper, tomato, and vine plants were assigned to either a treated or an untreated group for comparison. Gas exchange measurements were performed on nine mature leaves per treatment group at 0, 48, and 72 h after treatment with

Table 1. Stomatal conductance (*gsw*, in mol m^{-2} s^{-1}) and transpiration rate (*E*, in mmol H_2O $m^{-2}s^{-1}$) values determined for tomato, pepper, and vine plants at different times after treatment with SafeWax as compared to the control (CK). Different letters (a or b) indicate significant differences between treatments according to the ANOVA test[28] (p ≤0.05).

	Tomato				Pepper				Vine			
	gsw		*E*		*gsw*		*E*		*gsw*		*E*	
Interval after treatment, h	CK	SafeWax	CK	SafeWax	CK	SafeWax	CK	SafeWax	CK	SafeWax	CK	SafeWax
0	0.18 a	0.10 b	3.13 a	1.87 b	0.13 a	0.04 b	2.56 a	1.76 b	0.17 a	0.09 a	2.83 a	1.62 a
48	0.12 b	0.25 a	1.67 b	3.54 a	0.18 a	0.14 a	2.97 a	2.35 a	0.20 a	0.17 a	4.15 a	3.78 a
72	0.22 a	0.15 b	3.15 a	2.31 b	0.12 a	0.13 a	2.08 a	2.08 a	0.19 a	0.18 a	4.08 a	3.55 a

stearic acid-based SafeWax. The obtained results are summarized in **Table 1**. Immediately after treatment (0 h), both tomato and pepper plants treated with SafeWax showed a statistically significant reduction in stomatal conductance and transpiration rates. In the case of vine, lower values were also observed for both parameters after coating, yet without statistical significance.

At 72 h after treatment, the initial difference found for pepper plants disappeared, with subsequent measurements showing no statistically significant differences between coated and uncoated plants. This indicates no long-term impact of the SafeWax treatment on both parameters considered. In the case of tomato plants, higher values of stomatal conductance and transpiration rates were observed on coated leaves after 48 h (suggesting enhanced physiological activity), whereas levels below the control were measured after 72 h. For vine, the absolute difference between SafeWax-treated plants and the control (although not statistically significant) was greatest immediately after treatment and progressively decreased at 48 and 72 h. An initial reduction of stomatal conductance and transpiration, as observed for all three plants investigated, has also been reported in response to conventional pesticide application in previous studies. For example, Xia et al.[29] found a decrease of stomatal conductance in cucumber seedlings after a period of one day following the treatment with various chemical pesticides. This suggests that the initial response of plants to the SafeWax coating represents a level of stress similar to that caused by conventional pesticides. The subsequent fluctuations of *gsw* and *E* in the case of tomato plants may reflect an adaptive response that could be harnessed to enhance resilience to environmental stresses. Similar effects have been observed with other film-forming

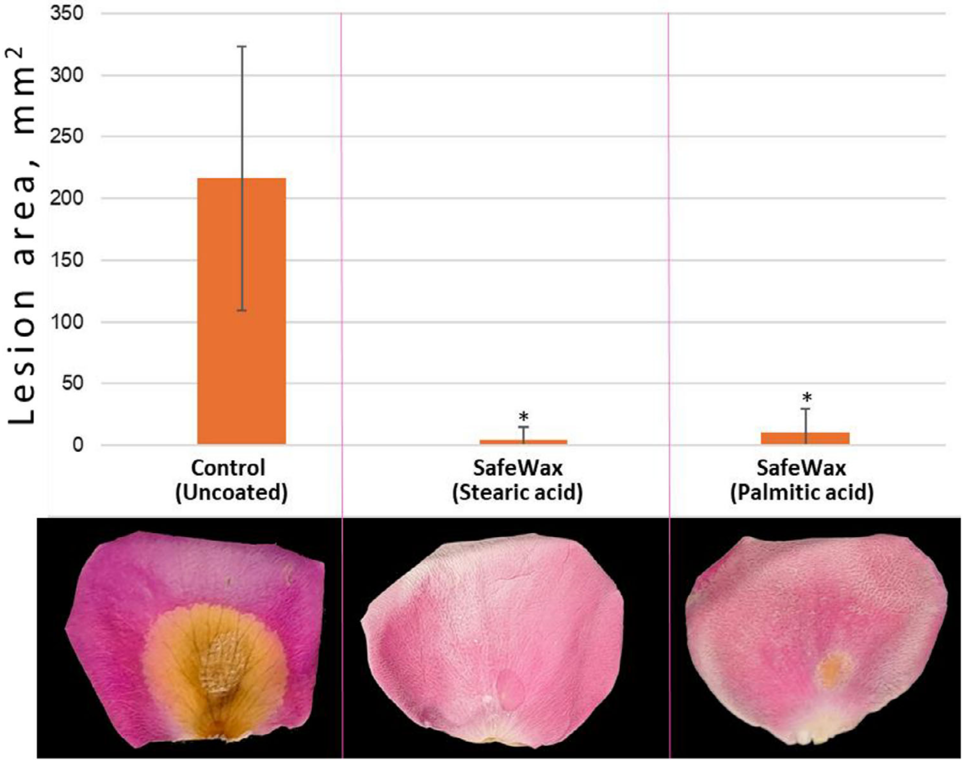


Figure 3. Proof of concept for the antifungal effect of SafeWax using the example of *B. cinerea* infection of rose petals that were coated with stearic or palmitic acid-based formulations. Top: Measured lesion areas. (*) indicates a significant difference compared to untreated samples (p-value ≤0.05) according to one-way ANOVA method.[28] Bottom: Corresponding photographs of the rose petals taken at 72 h after inoculation with *B. cinerea* spores.

Table 2. Thermal stability of SafeWax coatings. Wetting properties and surface roughness determined for coatings based on stearic or palmitic acid before and after heat treatment at 50 °C for 24 h.

	Stearic Acid-Based SafeWax		Palmitic Acid-Based SafeWax	
Parameter	Original	Heated	Original	Heated
CA [°]	165.1 ± 1.6	165.1 ± 1.6	157.6 ± 1.9	158.3 ± 2.2
CAH [°]	< 5	< 5	< 5	< 5
Sq [μm]	6.1 ± 0.5	5.8 ± 1.2	5.2 ± 0.3	5.4 ± 0.5

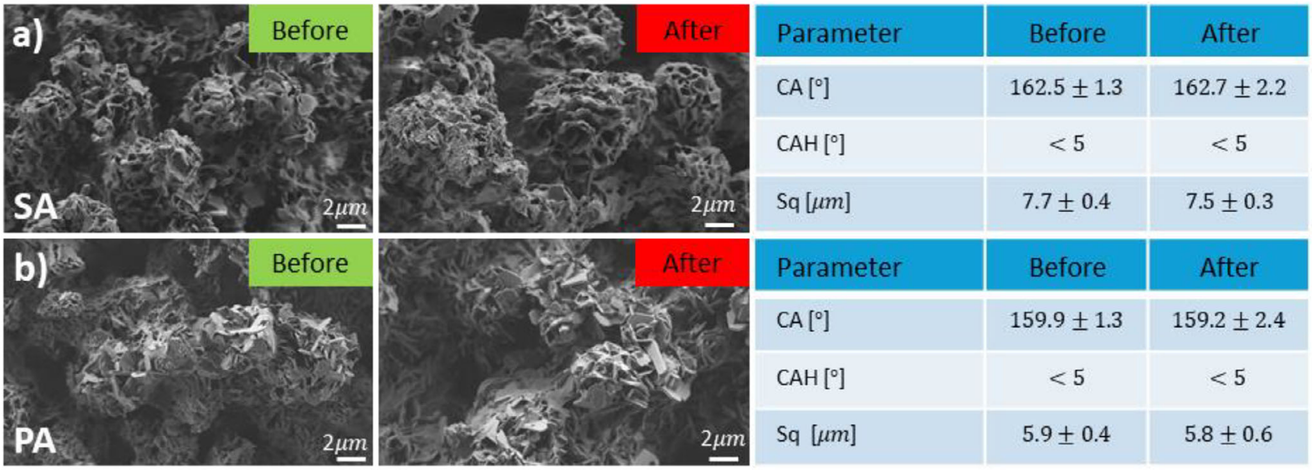
treatments, which were reported to modulate stomatal conductance and transpiration rates in different ways as depending on crop type, environmental conditions, and applied concentration.[30] In any case, our results for pepper and vine plants suggest that the SafeWax coating does not significantly affect stomatal conductance or transpiration rates. Future studies will aim to confirm and further evaluate the physiological shifts induced by SafeWax treatments, investigating whether temporary changes in stomatal conductance and transpiration rates could potentially translate into agronomic benefits under various environmental conditions.

To evaluate the antifungal efficacy of SafeWax, a series of explanta laboratory tests was performed using detached rose petals as a model system to assess the effect of the coating against *Botrytis cinerea* (*B. cinerea*),[31,32] a widespread necrotrophic fungus responsible for gray mold on more than 1400 plant species.[33] It predominantly affects grape, strawberry, and tomato crops, and is ranked as the second most important plant pathogen worldwide.[34,35] For evaluation, the rose petals were spray-coated at a volume of 1.5 mL per petal with SafeWax formulations based on stearic or palmitic acid. A 30 μL droplet of *B. cinerea* suspension, prepared as described in the Experimental section, was individually applied onto uncoated and coated petals, which were then incubated under humid conditions (90%) at room temperature in darkness. After waiting for 72 h, disease severity and progression were quantified by measuring the lesion area beneath and around the droplets, giving the results shown in **Figure 3**. It is evident that petals carrying a SafeWax coating exhibited significantly smaller areas of lesion compared to uncoated leaves. This experiment demonstrates that the coatings effectively delay the progression of *B. cinerea* infection (Figure 3).

Having established proof of concept for the physiological compatibility and antifungal efficacy of the SafeWax technology, we now turn to consider the stability of the coatings under relevant conditions. The resilience to sustained heat exposure was tested at an elevated temperature of 50 °C for 24 h with palmitic acid- or stearic acid-based SafeWax coatings applied on glass substrates. The temperature was chosen to simulate thermal conditions that could be encountered in some agricultural environments, such as during prolonged sun exposure in warm climates. After exsitu thermal treatment in air, the coatings were evaluated with respect to changes in their wetting properties (CA and CAH) and surface roughness characteristics (*Sq*). The results, summarized in **Table 2**, showed no notable changes in any of the determined parameters. This indicates that the superhydrophobic and microstructural characteristics of the SafeWax coatings were preserved despite the prolonged exposure to heat, as long as the temperature remained below the melting point of palmitic acid (62.9 °C). These findings suggest that SafeWax can maintain consistent antifungal performance and water-repellent behavior under thermal stress, thereby extending its lifespan and reducing the need for frequent reapplication.

UV resistance is another critical aspect of durability, particularly for coatings intended for outdoor use. To simulate prolonged exposure to sunlight under natural weather conditions, glass substrates coated with stearic or palmitic acid-based SafeWax formulation were illuminated with UVC radiation corresponding to ≈18 years of natural sunlight exposure[36] (see Experimental section). Comparative analyses of the wetting properties and surface roughness of the coatings before and after exposure revealed no significant degradation in the hydrophobicity and morphology of the coatings, as shown by the data presented in **Figure 4**.

Finally, we have tested the hypothesis that the superhydrophobic nature of SafeWax coatings could be beneficial for water harvesting by facilitating the collection of condensed water and dew on the leaf surface during nighttime hours. The self-cleaning



Parameter	Before	After
CA [°]	162.5 ± 1.3	162.7 ± 2.2
CAH [°]	< 5	< 5
Sq [μm]	7.7 ± 0.4	7.5 ± 0.3

Parameter	Before	After
CA [°]	159.9 ± 1.3	159.2 ± 2.4
CAH [°]	< 5	< 5
Sq [μm]	5.9 ± 0.4	5.8 ± 0.6

Figure 4. UV resistance of the SafeWax coatings. Left: High-resolution SEM images of coatings based on a) stearic acid (SA) and b) palmitic acid (PA) before and after exposure to 6 h of UV radiation. Right: Corresponding wetting properties and surface roughness values.

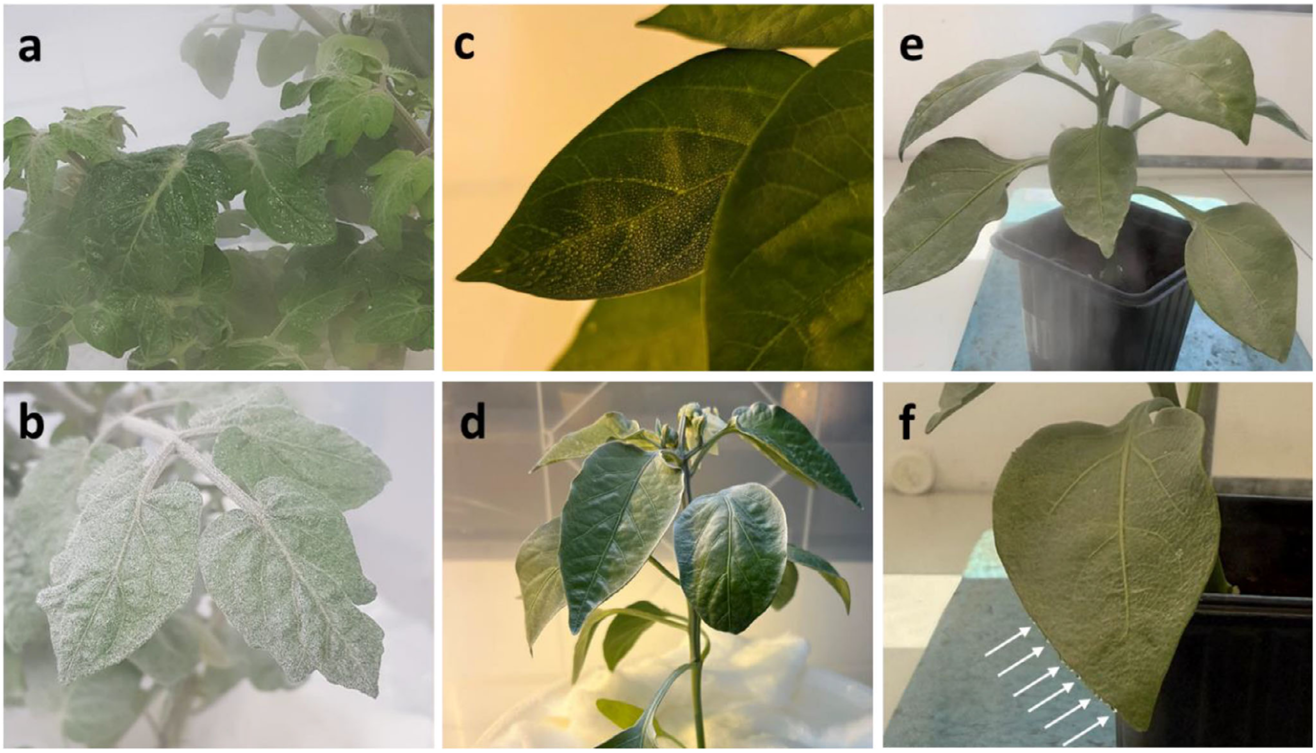


Figure 5. Water harvesting potential of SafeWax assessed on the tomato and pepper plants via exposure to high humidity. Images (a, b) show tomato plants: (a) without coating and (b) with SafeWax coating based on stearic acid. Images (c–f) show pepper plants: (c) without coating, (d) with stearic-acid based SafeWax, and (e, f) with palmitic acid-based SafeWax, all after exposure to near-100% humidity for 2 h. White arrows in (f) indicate the accumulation of water droplets at the edge of a coated pepper leaf, demonstrating the water harvesting behavior of SafeWax.

effect should allow water droplets to easily roll off the coated leaves and flow directly to the soil. This would enhance soil moisture levels and deliver water to the root system of the plant, thus providing an additional source of hydration. For experimental validation, tomato plants coated with stearic acid-based SafeWax and pepper plants coated with either stearic or palmitic acid-based SafeWax, as well as uncoated controls, were exposed to a near-100% humidity environment using a commercial humidifier over 2 h. Preliminary studies revealed distinct differences in behavior between the coated and uncoated leaves, as shown in **Figure 5**. In particular, dew formation was significantly delayed on the SafeWax-coated leaves, which remained essentially dry (Figure 5b,d–f), while water readily condensed on the uncoated ones (Figure 5a,c). Interestingly, several water droplets were observed accumulating at the edge of a coated pepper leaf (Figure 5f). As the abaxial sides of the foliage were not coated with SafeWax, water is effectively collected and can be shed to the soil, which highlights the water-harvesting potential of the technology.

These observations serve as a first indication of the potential of SafeWax to improve water harvesting. However, dedicated measurements are needed to quantify the differences in water collection between coated and uncoated plants, in order to confirm the ability of the technology to enhance plant hydration and resilience.

Taken together, the early experimental results reported in this section highlight the potential of SafeWax as a multifunctional coating that can provide antifungal protection, enhance water use efficiency, and support crop resilience to typical environmental stressor in agricultural systems. Further research is imperative to validate these effects, optimize the SafeWax formulation, and tailor the application process to meet the specific demands of the agricultural industry and end users.

2.5. Applications and Broader Benefits

Due to its multifunctional properties, SafeWax appears to be a highly promising alternative solution for a wide range of agricultural applications. Beyond the proven antifungal effect, the potential of technology to reduce water loss and offer (partial) protection against UV radiation increases its attractiveness particularly for regions experiencing drought or extreme temperatures. In principle, SafeWax can be applied to a wide variety of crops. Its versatility and ease of application should appeal to farmers seeking to reduce their reliance on chemical fungicides while aiming to maintain crop vitality and avoiding major additional costs related to antifungal products and their use in established agricultural processes. Beyond its promising performance in the protection of plants, SafeWax aligns with global efforts to promote more sustainable farming practices and directly supports the goals of the European Green Deal by reducing the need for chemical inputs and improving crop resilience to climate-related stressors. Furthermore, the fact that the raw materials required for SafeWax coatings are biobased and can be sourced from waste streams underscores the sustainability profile of this innovative technology. Although, so far, no tests have been performed to evaluate the potential of SafeWax coatings in other areas of application, it seems plausible to assume that they could be interesting for various surface-related challenges, such as biocide-free solutions to prevent biofilm formation on exterior walls of architecture or ship hulls.

2.6. Future Directions and Challenges

While the results of the initial SafeWax trials are highly promising, several fundamental challenges remain to be addressed before the technology can be widely adopted. These include questions related to the supply of raw materials and the production of the spray formulation at scales required for the agricultural market as well as at costs that ensure economic competitiveness. As in the case of other protective agricultural coatings, periodic reapplication of SafeWax will be necessary in order to maintain sufficient coverage and long-term efficacy, particularly as plants grow and develop new foliage with time. While the current study focuses on short-term efficacy, the required application frequency of SafeWax under field conditions as well as its antifungal efficacy upon reapplication are important factors that will be addressed in future research. Also, studies on potential long-term effects of SafeWax coating on plant physiology, soil health, microbial ecosystems, and beneficial organisms must be performed to exclude any significant detrimental influence. Although fatty acids are generally considered biodegradable and biocompatible, comprehensive assessments of possible environmental impact, including soil residue and carbon-nitrogen cycle analyses, are mandatory before use.

Apart from economic and ecologic aspects, it will also be important to further elucidate the mechanisms underlying the antifungal activity of SafeWax coatings and the factors contributing to the desired reduction of surface wettability and water retention at the leaf interface. Potential alterations of the microenvironments on the leaf surface, including local humidity and temperature gradients as well as evaporative dynamics, remain to be systematically studied. Once a deeper understanding of all these phenomena is achieved, the protective function and overall efficiency of SafeWax could be improved in a rational way.

The most critical aspect of the SafeWax technology as it now stands is the need for organic solvents with sufficient volatility to trigger fatty acids crystallization into the desired hierarchical structures upon evaporation. Although hazardous solvents like DEE can meanwhile be avoided and replaced by less problematic ones such as ethanol,[37] several concerns remain. First, the potential impact of the used organic solvent on the health of plant, soil, and fauna must be scrutinized. Second, special safety precautions will be necessary to account for dangers related to the flammability of the solvents and the exposure of workers to solvent vapor during the spray application. Third, the need for solvents may negatively affect the overall sustainability of the technology (e.g., via their product carbon footprint) and could also impair cost competitiveness. Hence, the most urgent innovation required at the moment is a technology for a solvent-free formulation of SafeWax, ideally with equal versatility and performance. Both solvent-based and solvent-free formulations will have to be refined to enhance their efficacy across different crop types and environmental conditions.

If reformulation toward more sustainable compositions can be realized, SafeWax is anticipated to exhibit a more favorable environmental profile, particularly in comparison to conventional copper-based fungicides, which are known for their long-term ecological toxicity. It should further be explored as to whether SafeWax can be combined with other sustainable agricultural practices (such as organic farming or integrated pest management) and/or applied together with conventional pesticides in formulations that require significantly lower pesticide dosages to achieve the same level of crop protection.

3. Conclusion

SafeWax is an innovative technology with the potential to become a breakthrough in the field of sustainable crop protection. Harnessing the principles of biomimicry, SafeWax has been designed as a spray-on technique that leaves a self-assembled coating of fatty acid crystals with superhydrophobic properties on plant surfaces. Preliminary tests have shown that these coatings may help reduce the extent of *B. cinerea* infection, presumably by hindering spore adhesion and reducing the surface moisture required for germination. In addition, SafeWax provides plants with protection against environmental stress factors like high temperature or UV radiation and may contribute to more efficient water collection in soil and root systems. Thus, SafeWax technology can be considered as an eco-friendly and multifunctional solution that may replace conventional pesticides in times of increasing demands and challenges in global architecture as posed by climate change and sustainability roadmaps.

4. Experimental Section

Materials: Stearic acid (97%, Merck, Germany), palmitic acid (99%, Acros Organics, USA), and arachidic acid (99%, AA-Blocks, USA) were used for the coating preparation. Diethyl ether (DEE, stab. BHT, Bio-Lab, Israel) was used as a solvent.

Methods—Preparation of Formulations and Coatings: Coating formulations were prepared by dissolving stearic, palmitic, or arachidic acid at a concentration of 20 mg mL^{-1} in DEE (2.8 wt.%), with continuous stirring until complete dissolution was achieved. Coatings were fabricated by spray deposition using a commercially available dye spray gun, connected to an air compressor operating at a pressure of 6 bar.

Methods—Characterization of the Coatings: Morphology: Morphology of the coatings was studied using 1 KV beam of high-resolution scanning electron microscope (HR-SEM) Zeiss Ultra Plus FEG-SEM. Prior to the imaging, samples were coated with a thin carbon layer (≈several nanometers) to ensure surface conductivity using a designated carbon coater.

Wetting Properties: Wetting Properties of the coatings were characterized by contact angle (CA) and contact angle hysteresis (CAH) measurements, which were performed using an Attension Theta Lite tensiometer and high-purity water droplets of 7 µL volume.

Surface Roughness (*Sq*): *Surface Roughness* values were measured using a dynamic confocal microscope Sensofar S Neox; data processing was performed using SensoVIEW 2.4.1.0 software.

To ensure reproducibility, foliar coating characterization tests were conducted on various plant species, involving several dozens of plants and hundreds of leaves.

Methods—Thermal Treatments and UV Resistance: Thermal stability as well as UV resistance experiments were performed on glass substrates of size of 7.5 × 2.5 cm^2 spray-coated with 10 mL of either stearic-acid or palmitic-acid based SafeWax solution. Thermal treatment was performed using a Jeio Tech OV-11 oven at 50 °C for 24 h. For UV experiments, the coated surfaces were exposed to UVC radiation at a flux of 42.14 mJ cm^{-2} and a wavelength of 256 nm for 6 h. Both tests were performed on sets of 5 substrates per formulation. CA, CAH, Sq measurements were taken at three different points on each substrate.

Methods—Photosynthetic Activity Assessment: Stomatal conductance (gsw, mol H_2O m^{-2} s^{-1}) and transpiration rate (E, mmol H_2O m^{-2} s^{-1}) in pepper, tomato, and vine plants were evaluated under controlled greenhouse conditions following the foliar application of stearic-acid based SafeWax onto a total of six pepper plants, four tomato plants, and six vine plants. A volume of 80 mL of the formulation was applied per plant to perform coating. Treated and untreated groups were defined for comparative analysis. Gas exchange measurements were performed using the LI-COR LI-600 Porometer/Fluorometer on nine mature leaves per treatment group at 0, 48, and 72 h after treatment. The analyzed leaf area is ≈2 cm^2, as defined by the standard clamp integrated into the sensor head.

Methods—Antifungal Study: Spores of *B. cinerea* (isolate B05.10), were cultured in potato dextrose broth (PDB, Sigma–Aldrich, Israel) medium for 7 days. Following this, fungal spores were harvested and dispersed in 0.9% saline using a hemocytometer at a final concentration of 10^4 spores mL^{-1}. Milli-Q water (18.2 MΩ·cm) were used for the experiment. Studies were performed on 45 petals in total. Coating was performed using 1.5 mL of the formulation based on stearic or palmitic acid applied per petal. Lesion areas were measured using ImageJ software.[38]

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

bioinspired, multifunctional materials, superhydrophobic, sustainable agriculture

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