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Environmental Pollution Impacts and Sustainable Greenhouse Drying Systems in Agricultural Processing: An Updated Comprehensive Review

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ABSTRACT

Greenhouse drying systems are increasingly recognized as a strategic response to postharvest loss, high thermal energy demand, and the growing environmental burdens associated with conventional drying operations. Building upon the earlier uploaded review and integrating the recent literature contained in the attached RIS file, this article reassesses greenhouse drying through the wider lens of environmental pollution, cleaner production, product safety, occupational exposure, and circular resource use. The reviewed evidence indicates that drying remains one of the most energy-intensive operations in agricultural and biomass processing, yet it also offers significant opportunities for decarbonization through solar utilization, hybrid heating, heat recovery, improved ventilation control, and low-emission system design. Recent literature further shows that the sustainability of drying systems cannot be judged solely by drying kinetics or thermal efficiency. Environmental performance must also account for gaseous emissions, airborne particles, microplastic release, noise, residue valorization, and life-cycle burdens. Across the uploaded source set, solar and greenhouse-assisted systems consistently demonstrate strong potential to reduce dependence on fossil-derived heat, support decentralized processing, and improve the environmental profile of biomass, sludge, food waste, digestate, and agricultural residues. At the same time, the literature highlights unresolved concerns related to ammonia release, indoor air pollution, pollutant transport, material contamination, and worker exposure. This review synthesizes those findings into a six-pillar framework for next-generation greenhouse dryers: energy integration, drying performance, product quality and safety, environmental pollution control, circularity, and smart monitoring. It concludes that future greenhouse dryers should evolve from simple passive enclosures into intelligent, hybrid, low-emission, and pollution-aware processing platforms capable of supporting climate-resilient and sustainable agricultural systems.

Keywords: greenhouse drying; environmental pollution; solar-assisted drying; sustainable postharvest processing; cleaner production; agricultural residue valorization; drying emissions

INTRODUCTION

Drying is one of the oldest and most indispensable preservation methods in agriculture and agro-industry. It reduces moisture content to safer storage levels, limits microbial deterioration, stabilizes biological materials, lowers transportation mass, and supports downstream processing. Despite these benefits, drying is also one of the most energy-intensive operations in food and biomass processing, often accounting for a substantial share of thermal energy use and associated greenhouse gas emissions. This dual character of drying—as both a technical necessity and an environmental burden—has driven sustained interest in alternative drying systems, particularly greenhouse and solar-assisted dryers.

The earlier review attached as dryer established the relevance of improved drying technologies for agricultural materials and emphasized the importance of reducing energy consumption and environmental burden. The newer literature included in the uploaded greenhouse RIS file strengthens that concern and expands it in a decisive direction. Greenhouse drying is no longer only a matter of renewable heat substitution or passive solar utilization. It must also be understood as part of a broader environmental transition in which drying systems are evaluated for energy efficiency, emissions, occupational safety, product contamination risks, material circularity, and overall environmental performance.

Recent studies illustrate this wider scope. Chojnacka et al. (2021) argue that drying is a major energy-consuming process that must be modernized using hybrid techniques, renewable energy, and improved energy management. Berg et al. (2021) show that drying of digestate can lead to substantial nitrogen losses and ammonia emissions, revealing that dryer performance cannot be assessed solely through moisture reduction. Dramé et al. (2023) demonstrate that solar drying can provide a viable and lower-risk alternative for sewage sludge management. Jeong et al. (2023), Sun et al. (2025), Winkler et al. (2022), and Eichler et al. (2024) expand the discussion even further by showing that drying environments can be associated with ultrafine particles, gaseous pollutants, microplastic fibers, PFAS reservoirs, and indoor exposure pathways.

For greenhouse dryers, this matters profoundly. A greenhouse dryer is not simply a transparent chamber that traps solar radiation. It is a coupled solar–thermal–mass transfer–air quality–materials system whose performance depends on radiation capture, airflow pattern, humidity evacuation, product loading density, enclosure properties, auxiliary heating strategy, ambient climate, and operational control. When these elements are poorly designed, greenhouse dryers may underperform in drying rate, product quality, and environmental hygiene. When they are well integrated, they can serve as low-carbon, decentralized, and multifunctional processing platforms.

The environmental pollution dimension is especially relevant today. Climate change is producing warmer and drier conditions in many regions, which may increase passive drying potential but also intensify air pollution episodes, fire-related aerosols, water stress, and occupational heat exposure (El-Sherif, 2025; Hao et al., 2025; Islam et al., 2024; Zheng et al., 2023). Simultaneously, agricultural and agro-industrial sectors are being pressured to reduce emissions, valorize residues, and transition toward cleaner production and circular bioeconomy models. Greenhouse drying sits at the intersection of these shifts.

This updated review responds to those developments. It builds upon the uploaded dryer literature set and integrates the recent evidence represented in greenhouse.ris to produce a new publication-oriented synthesis. The review has four objectives. First, it repositions greenhouse drying within a wider framework of environmental pollution and sustainability. Second, it identifies the key technological and environmental advances represented in the uploaded source pool. Third, it extracts cross-cutting lessons on emissions, product quality, circularity, occupational exposure, and system design. Fourth, it proposes an updated agenda for next-generation greenhouse drying systems.

The article is organized into the requested structure: abstract, keywords, introduction, research methodology, results and discussion, conclusions and suggestions, and bibliography. Although the prompt contains one instruction not to provide a list of references, the later instruction explicitly requires a bibliography based on the attached RIS file. In this article, the final and more specific formatting request is followed.

METHODS

1. Review design

This article was prepared as an integrative and structured review using only the uploaded source materials: the earlier literature corpus in dryer and the recent bibliography in greenhouse.ris. No references were added from the web or other external databases.

2. Nature of the source base

The uploaded dryer file functions primarily as a literature extraction set containing article records, metadata, and abstracts rather than a finished narrative review. The uploaded greenhouse RIS file provides structured bibliographic information for the updated source pool. Together, these files offer sufficient material for an updated synthesis focused on greenhouse drying, environmental pollution, and sustainable processing.

3. Screening logic

Because the uploaded source pool is interdisciplinary, a relevance hierarchy was used:

- **Direct relevance:** studies explicitly addressing drying technologies, solar drying, grain drying, sludge drying, digestate drying, food waste dehydration, or dryer performance.
- **Indirect relevance:** studies focused on pollution, air quality, particulate emissions, microplastics, indoor pollutants, PFAS, or environmental risk in drying-related contexts.
- **Contextual relevance:** studies that do not examine greenhouse dryers directly but help explain sustainability pressures, climate risks, and cleaner production pathways relevant to greenhouse dryer design.

4. Thematic synthesis approach

The reviewed studies were synthesized into six thematic categories:

1. modernization of drying technologies;
2. greenhouse and solar drying as low-carbon strategies;
3. environmental pollution implications of drying systems;
4. product quality, residue transformation, and contamination risks;
5. circularity, resource recovery, and waste valorization;
6. future design directions for smart, low-emission greenhouse dryers.

5. Citation and bibliography handling

In-text citations were formatted in APA author–date style as requested. Bibliography entries were reconstructed from the uploaded RIS file. Citation integrity was maintained by limiting all attributions to the uploaded files only.

6. Scope and limitations

This review has several limitations. First, not all uploaded studies focus directly on greenhouse agricultural dryers. Second, some cited sources are used conceptually because they illuminate environmental pollution, emissions, or health-related aspects of drying systems rather than greenhouse performance per se. Third, the source pool does not equally cover all emerging subtopics such as PCM integration, advanced sensors, digital twins, and crop-specific greenhouse dryer optimization. These are therefore treated as future research opportunities rather than supplemented with external references.

RESULT AND DISCUSSION

1. Drying technology is being redefined by environmental performance

One of the clearest insights from the uploaded literature is that drying is no longer evaluated primarily in terms of moisture removal efficiency. Instead, it is increasingly judged through the combined lenses of energy use, emissions, environmental burden, and cleaner production. Chojnacka et al. (2021) show that drying is integral to preserving grains and agricultural products, but also stress that it is among the most energy-consuming operations in food production. Their review points to hybrid methods, renewable sources, and energy recovery as essential pathways toward more sustainable drying.

This shift is highly relevant to greenhouse dryers. Traditionally, greenhouse drying has often been promoted simply because it uses solar radiation. However, the uploaded literature suggests that renewable heat capture is only one part of sustainability. A greenhouse dryer that performs poorly in humidity removal, product protection, or pollution control may still create environmental and quality problems even if its direct fuel use is lower. Therefore, the modernization of greenhouse drying must be based on systems integration rather than solar collection alone.

The uploaded studies further suggest that drying technology is moving toward hybridization. Chojnacka et al. (2021) highlight microwave-, infrared-, and ultrasound-assisted drying as examples of process intensification that can lower non-renewable energy demand. Although these are not greenhouse systems by themselves, they imply a useful principle for greenhouse dryer development: solar gain may be ideal for bulk moisture removal, while selective auxiliary technologies may improve late-stage drying, product uniformity, hygiene, or operational stability.

2. Greenhouse and solar drying as low-carbon alternatives

The literature strongly supports the role of greenhouse and solar-assisted drying as low-carbon processing alternatives. Dramé et al. (2023) demonstrate that a sustainable solar drying system for municipal sewage sludge can achieve very high solids content while maintaining low potential ecological risk. This finding is significant because it shows that solar drying is not limited to fruits or grains; it can also be used for wet residues and semi-solid wastes, expanding the practical relevance of greenhouse drying systems.

Quispe et al. (2019) offer another important contribution through life-cycle assessment of rice husk as an energy source. Their results indicate that agricultural residues can substantially reduce global warming, acidification, and eutrophication burdens compared with coal, although water depletion trade-offs remain. For greenhouse dryers, this implies that auxiliary heating systems based on agricultural residues may strengthen sustainability if carefully integrated. In other words, the most promising greenhouse dryers may not be purely passive systems, but hybrid solar–biomass systems optimized for minimal environmental burden.

Amir et al. (2025) reinforce this perspective by showing how drying and subsequent handling can support valorization of seaweed industrial by-products. Similarly, Khalida et al. (2022) argue that dehydration of food waste is an important step toward more sustainable waste management, even though post-drying treatment is still necessary. Together, these studies suggest that greenhouse drying can function as a platform technology within broader circular processing chains rather than as a stand-alone preservation tool.

3. Energy efficiency, heat recovery, and system integration

The uploaded literature repeatedly indicates that energy performance improves when drying systems are integrated with heat recovery and broader process optimization. Chojnacka et al. (2021) explicitly identify proper energy management, heat recovery, and moisture removal from drying air as critical challenges. Variny et al. (2021), while studying compression heat management in a cryogenic air separation context, provide a useful systems-level lesson: waste heat utilization can meaningfully reduce energy consumption and emissions.

For greenhouse drying, this suggests that the main design challenge is not only solar heat capture but coordinated control of temperature, humidity, and airflow. In many climates, greenhouse dryers underperform because trapped humidity suppresses further evaporation. Under such conditions, raising temperature alone produces diminishing returns. Instead, performance improvement requires carefully managed ventilation, air recirculation, dehumidification strategies, and possibly heat recovery from exhaust streams.

A modern greenhouse dryer should therefore be interpreted as a thermo-hygrometric control system. From the uploaded literature, several integration priorities emerge:

- selective venting based on humidity thresholds rather than simple temperature rise;
- recirculation strategies that retain sensible heat while removing moisture;
- auxiliary renewable heat for periods of weak solar radiation;
- thermal storage to reduce interruption during transient weather;
- and process-level coupling with residue-to-energy pathways.

These strategies are especially relevant in humid tropical regions, where greenhouse enclosures can quickly become moisture saturated. The literature implies that future greenhouse dryers must be designed for local climate realities rather than generic solar assumptions.

4. Environmental pollution is a central but under-discussed dimension of drying systems

A major contribution of the newer uploaded literature is the widening of the pollution perspective. Drying systems are often described as environmentally beneficial when they reduce wet spoilage, lower fuel use, or stabilize residues. Yet several studies show that drying can also generate or intensify specific environmental pollution problems.

Berg et al. (2021) found that laboratory-scale fixed-bed drying of digestate led to total nitrogen reductions of 29–42% and ammonium nitrogen losses of 92%. These results are crucial because they reveal that drying may shift pollutants from a wet matrix into the gaseous phase. In practical greenhouse dryers used for digestate, sludge, or manure-related materials, uncontrolled volatilization may undermine nutrient recovery and cause ammonia-related environmental and occupational impacts.

Lubitz et al. (2023) introduce another pollution dimension by showing that grain dryers can generate significant environmental noise emissions. Although noise is rarely considered in dryer design studies, it matters for rural communities, on-farm labor, and facility siting. Their work suggests that pollution-aware greenhouse drying should also account for mechanical noise when fans or blowers are integrated.

Jeong et al. (2023) demonstrate that clothes dryers can act as episodic indoor sources of ultrafine particles. While the studied context is residential, the broader implication is that heated air movement, combustion-based auxiliaries, and drying-induced aerosol dynamics deserve more attention in greenhouse dryer research. Sun et al. (2025) further show that gas clothes dryers are associated with increased indoor NO2 levels, while Winkler et al. (2022) reveal the release of microplastic fibers from dryer exhaust filters. Eichler et al. (2024) show that dryer lint can also function as a PFAS reservoir in homes. Together, these findings indicate that drying systems can be environmental pollutant nodes, affecting air quality and exposure pathways beyond the immediate process chamber.

For agricultural greenhouse dryers, this does not mean the same pollution profiles will automatically occur. However, the analogy is important: greenhouse dryer design should proactively consider pollutants generated by combustion, heated airflow, residues, fine particulates, or degraded materials. Future agricultural dryer studies should therefore include pollutant monitoring alongside conventional performance metrics.

5. Product quality and environmental sustainability must be addressed together

One recurring challenge in sustainable drying is the tension between fast moisture reduction and preservation of product quality. Chojnacka et al. (2021) highlight the need to protect bioactive substances while reducing energy use. This tension is central to greenhouse drying because the solar environment can fluctuate strongly, causing temperature peaks, non-uniform airflow, and uneven drying histories.

The uploaded literature suggests that a greenhouse dryer designed only for energy saving may sacrifice color, texture, nutrient stability, or drying uniformity. Conversely, a highly controlled system may require more auxiliaries and thus diminish its environmental advantage. The solution implied by the literature is not to maximize one objective at the expense of the other, but to adopt a multi-criteria design framework.

For some products, slow drying at moderate temperatures may protect quality but increase exposure time to contamination or microbial risk. For others, faster finishing stages may be needed to protect nutrient or sensory attributes. This reinforces the value of hybrid greenhouse dryers in which solar energy performs most of the moisture removal but controlled finishing is used where necessary.

6. Climate change intensifies the need for resilient greenhouse dryers

Several uploaded studies show that warmer and drier conditions are becoming more common in different environments (El-Sherif, 2025; Islam et al., 2024; Mu et al., 2023; Zheng et al., 2023). These trends matter for greenhouse drying in at least three ways.

First, rising temperatures and reduced humidity can increase passive drying potential in some settings, potentially improving solar dryer performance. Second, stronger climatic variability can reduce reliability by introducing unexpected rainfall, extreme heat, wind-driven dust, wildfire smoke, or poor ambient air quality. Third, climate change creates new occupational and environmental health burdens, especially in hot semi-enclosed systems.

El-Sherif (2025) emphasizes that hotter and drier conditions intensify environmental and occupational health risks. Islam et al. (2024) show that warmer, drier urban conditions are linked with higher particulate matter burdens. Hao et al. (2025) demonstrate how transported smoke from crop residue burning can dominate particulate pollution and health risks in northern Indian cities. These findings imply that greenhouse dryers must be understood within the ambient environmental context. A dryer operating during regional smoke episodes, for example, may expose products or workers to external contamination unless filtration or enclosure strategies are improved.

Thus, climate-resilient greenhouse dryers must address more than solar gain. They must also protect products and operators from heat stress, pollutant ingress, and climate-driven variability in ambient air quality.

7. Circularity and residue valorization expand the role of greenhouse drying

Another major theme in the uploaded literature is circularity. Drying is repeatedly presented as a gateway operation that enables reuse, recycling, energy recovery, or safer transport of wet residues. Dramé et al. (2023) frame solar drying as a lower-risk sludge management approach. Amir et al. (2025) use drying as part of a valorization pathway for seaweed by-product. Khalida et al. (2022) discuss dehydration as a critical step in food waste management. Quispe et al. (2019) show how agricultural residues can serve as low-impact energy resources.

These studies suggest that greenhouse drying systems should be assessed not only for what they do to primary agricultural products, but also for how they help transform side-streams into useful resources. A multifunctional greenhouse dryer may dry crops in one season, residues in another, and organic waste streams in another, improving utilization and economic viability. This multifunctionality is particularly attractive in rural contexts where capital expenditure must be justified across multiple value chains.

At the same time, circularity must not become a justification for ignoring pollution. For example, digestate or sludge drying may improve transportability and valorization potential, but emissions of ammonia, particulates, or odors must still be managed. Therefore, circular greenhouse dryers should be designed as closed-loop systems with environmental safeguards rather than simple solar evaporation structures.

8. Pollution-aware design principles for next-generation greenhouse dryers

The uploaded literature supports a reframing of greenhouse dryer design around environmental pollution impacts. Based on the synthesis, six design principles emerge.

First, pollution prevention should be integrated at the design stage. Dryer design should anticipate ammonia, odors, particulates, combustion gases, and material-derived contaminants rather than addressing them after deployment.

Second, ventilation should be intelligent rather than purely passive. Because moisture removal and pollutant control often depend on airflow, greenhouse dryers should use monitored, staged, or demand-based ventilation where possible.

Third, hybrid energy systems should minimize total burden, not only direct fuel use. Solar gain may be combined with biomass residues, heat recovery, or thermal storage, but those additions should be evaluated through environmental and life-cycle criteria.

Fourth, product and worker protection should be co-optimized. This includes not only thermal quality and contamination control, but also heat stress mitigation and exposure reduction for operators.

Fifth, residue-specific operation is essential. Drying food, grain, sludge, digestate, food waste, and industrial by-products requires different contamination safeguards and emission controls.

Sixth, monitoring should move beyond temperature and moisture. Pollution-aware greenhouse dryers should incorporate or at least be studied with additional indicators such as ammonia, particulates, air exchange rate, odor potential, or noise.

These principles collectively move greenhouse drying closer to a cleaner production model.

9. Integrating environmental pollution assessment into performance evaluation

The uploaded sources suggest that greenhouse drying research should adopt a broader indicator system. Traditional evaluation typically includes moisture content, drying rate, thermal efficiency, collector efficiency, specific energy consumption, and drying time. These remain important, but they are insufficient for a pollution-oriented review.

A more complete greenhouse dryer assessment should include at least four additional dimensions. The first is **air emissions**, especially where biomass combustion or drying of nitrogen-rich materials is involved. The second is **particulate and aerosol behavior**, including dust, smoke ingress, and product-associated particulates. The third is **occupational conditions**, such as temperature stress, pollutant exposure, and acoustic burden. The fourth is **life-cycle environmental burden**, including upstream material choice, auxiliary energy source, and end use of dried output.

This integrated assessment logic aligns with the broader trends visible in the uploaded literature. Quispe et al. (2019) and Chojnacka et al. (2021) point toward life-cycle and cleaner-production thinking. Berg et al. (2021) emphasize emission loss from the product itself. Lubitz et al. (2023) show that a nontraditional indicator such as noise can still be environmentally relevant. Sun et al. (2025), Jeong et al. (2023), Winkler et al. (2022), and Eichler et al. (2024) reinforce that dryers can shape exposure pathways. Therefore, pollution-aware greenhouse dryer research should treat performance as a multi-domain construct.

10. Materials, enclosure design, and contamination pathways

An often-overlooked issue in greenhouse dryer design is the role of materials. The uploaded literature does not provide a dedicated greenhouse cover-material comparison, but it does provide important conceptual evidence that dryer-associated materials can influence environmental quality. Winkler et al. (2022) show that dryers can release polyester-based microplastic fibers, while Eichler et al. (2024) show that dryer lint can accumulate PFAS-related compounds. Although these studies are residential and textile-oriented, they indicate a broader need for caution: enclosure liners, trays, synthetic covers, insulation materials, and seals used in greenhouse dryers may influence contamination risks over time, particularly under repeated heating and UV exposure.

This issue is especially relevant when greenhouse dryers are intended for high-value food products, medicinal plants, seeds, or nutraceutical materials. It also matters in hotter climates, where elevated surface temperatures may accelerate material degradation. Future greenhouse dryer work should therefore pay greater attention to material selection, durability under solar exposure, and contamination-safe design.

11. Greenhouse dryers in decentralized and rural systems

Another implication of the uploaded literature is that greenhouse dryers are especially suitable for decentralized applications. Solar drying of sludge (Dramé et al., 2023), valorization of by-products (Amir et al., 2025), and food waste dehydration (Khalida et al., 2022) all point to the practicality of lower-energy drying in contexts where centralized industrial equipment may not be economically viable.

This has important implications for agricultural regions where postharvest losses remain high due to limited access to modern drying infrastructure. A greenhouse dryer can offer several advantages in such environments: lower operating cost, reduced dependence on external fuel, adaptability to multiple feedstocks, and compatibility with circular reuse pathways. However, the same decentralized settings may also face limitations in monitoring, maintenance, and pollution control. Therefore, appropriate design simplification must not compromise environmental safety.

The literature suggests that the best pathway may lie in **intermediate-complexity systems**: more advanced than purely passive enclosures, but still robust, affordable, and locally maintainable. Such systems may combine solar gain, forced convection, limited automation, modular filtration, and residue-specific operating protocols.

12. Relationship between environmental pollution and greenhouse dryer legitimacy

The title emphasis on environmental pollution is not merely rhetorical. The uploaded evidence suggests that greenhouse drying will increasingly be judged by how convincingly it reduces pollution burdens compared with conventional alternatives. In other words, the legitimacy of greenhouse drying as a sustainable technology depends on its ability to demonstrate real environmental improvement.

This means greenhouse dryers should be compared against several reference cases, not only open-air drying or fuel-fired dryers. Relevant benchmarks include: uncontrolled waste decomposition, open burning of residues, electrically heated batch dryers, direct combustion dryers, and untreated wet waste disposal. In many of these comparisons, greenhouse drying is likely to perform favorably. However, without explicit measurement and transparent methodology, such advantages remain assumed rather than proven.

The next phase of greenhouse drying research must therefore move from promotional generalizations to evidence-based sustainability claims. That transition will strengthen the scientific credibility of the field and improve its standing in top-tier journals.

13. Summary tables

Table 1. Key themes in the recent literature relevant to greenhouse drying and environmental pollution

Theme	Main focus	Relevance to greenhouse drying	Key implication	Ref.
Drying modernization	Hybrid, renewable, energy-efficient drying	Provides conceptual foundation for improved greenhouse dryer design	Greenhouse dryers should evolve into hybrid systems with better control	Chojnacka et al. (2021)
Solar drying for wet residues	Solar drying of sludge and associated ecological risk	Extends greenhouse drying relevance beyond crops	Solar drying can support safer decentralized residue management	Dramé et al. (2023)
Nitrogen and ammonia loss	Emissions during digestate drying	Highlights pollution risk in wet biomass drying	Emission control is essential for nutrient-rich residues	Berg et al. (2021)
Residue-to-energy sustainability	Life-cycle assessment of rice husk energy	Supports auxiliary renewable heat for greenhouse dryers	Hybrid solar–biomass systems may reduce carbon burden	Quispe et al. (2019)
Indoor emissions from dryers	Ultrafine particles and gaseous pollutants	Warns that drying systems can affect air quality	Agricultural dryers should also be studied as emission sources	Jeong et al. (2023); Sun et al. (2025)
Material-derived contaminants	Microplastic fibers, PFAS in drying environments	Broadens environmental pollution perspective	Dryer materials and lint/particulate pathways require attention	Winkler et al. (2022); Eichler et al. (2024)

Table 2. Environmental pollution issues associated with drying-related systems

Pollution issue	Reported pathway	Likely relevance to greenhouse/agricultural dryers	Monitoring or mitigation need	Ref.
Ammonia release	Volatilization during drying of digestate	High for manure-, sludge-, or digestate-based drying	Gas monitoring, airflow control, adsorption/scrubbing	Berg et al. (2021)
Ultrafine particles	Episodic emissions during drying-related indoor sources	Possible where heated airflow and combustion coexist	Aerosol measurement, filtration, combustion optimization	Jeong et al. (2023)
Nitrogen dioxide	Gas appliance association in indoor drying environments	Relevant for auxiliary fossil-fuel burners	Cleaner heating, separation of combustion air, ventilation	Sun et al. (2025)
Microplastic fiber release	Dryer exhaust and lint	Possible if polymeric textiles or plastics are dried/used	Material choice, exhaust trapping, maintenance	Winkler et al. (2022)
PFAS accumulation	Dryer lint and household reservoirs	Conceptually relevant to contaminated materials	Source control, material screening, exposure assessment	Eichler et al. (2024)
Noise pollution	Fan/blower and dryer configuration	Relevant to active greenhouse dryers	Acoustic design, barriers, equipment choice	Lubitz et al. (2023)

Table 3. Sustainability opportunities for greenhouse dryer development

Opportunity area	Mechanism	Expected benefit	Major caveat	Ref.
Solar heat utilization	Direct capture of incident radiation	Lower direct fuel demand and operational cost	Weather variability and humidity accumulation	Dramé et al. (2023); Chojnacka et al. (2021)
Hybridization	Solar + auxiliary	Improved reliability	Added complexity	Chojnacka et al.

	renewable or efficient heating	and finishing quality	and capital cost	(2021); Quispe et al. (2019)
Heat recovery	Reuse of sensible/ latent energy from process air	Higher energy efficiency and lower emissions	Requires design sophistication	Chojnacka et al. (2021); Variny et al. (2021)
Residue valorization	Drying as pre-treatment for reuse/recycling	Supports circular bioeconomy pathways	Pollution control still required	Amir et al. (2025); Khalida et al. (2022)
Climate adaptation	Use under warmer/drier conditions	Potentially enhanced passive performance	Exposure to smoke, dust, and heat stress may rise	El-Sherif (2025); Zheng et al. (2023); Hao et al. (2025)
Cleaner production	Lower fossil fuel use, lower wet waste burden	Reduced environmental footprint	Full life-cycle assessment still needed	Chojnacka et al. (2021); Dramé et al. (2023)

Table 4. Proposed framework for next-generation greenhouse dryers

Pillar	Design priority	Indicators	Expected outcome	Ref.
Energy integration	Solar gain, hybrid auxiliaries, heat recovery	Specific energy use, solar fraction, fuel substitution	Lower carbon and operating cost	Chojnacka et al. (2021); Quispe et al. (2019)
Drying performance	Stable temperature–humidity–airflow control	Drying rate, uniformity, final moisture	Higher productivity and consistency	Chojnacka et al. (2021)
Product quality and safety	Moderate thermal exposure, contamination protection	Nutrient retention, color, microbial safety	Better market value and safer products	Chojnacka et al. (2021); Macher (2025)
Pollution control	Emission-aware operation and ventilation	Ammonia, particulates, NO2, odor, noise	Lower environmental and occupational burden	Berg et al. (2021); Jeong et al. (2023); Sun et al. (2025); Lubitz et al. (2023)
Circularity	Residue drying, reuse, and valorization pathways	Reuse rate, waste diversion, by-product value	Better resource efficiency	Dramé et al. (2023); Amir et al. (2025); Khalida et al. (2022)
Smart monitoring	Sensor-driven environmental control	Temperature, RH, airflow, emissions	More adaptive and climate-resilient operation	inferred from the reviewed source set

14. Research gaps

The uploaded literature reveals several research gaps that should guide future work. First, greenhouse drying studies still under-address environmental pollution indicators. Most research emphasizes temperature, humidity, moisture ratio, and thermal efficiency, but fewer studies quantify particulate emissions, ammonia, combustion gases, odors, or contaminant deposition.

Second, there is limited evidence on how greenhouse dryers interact with residue-specific pollution pathways. Drying crops, food waste, digestate, sludge, and industrial by-products cannot be treated as equivalent problems because their emissions, contamination hazards, and safe handling requirements differ substantially.

Third, life-cycle assessment remains insufficiently integrated into greenhouse dryer research. Studies such as Quispe et al. (2019) show the value of environmental system-level thinking, but many dryer studies still stop at energy balance or drying kinetics.

Fourth, the human exposure dimension requires more attention. The indoor air and dryer-emission studies in the uploaded literature show that drying systems can influence health-related exposure pathways, yet this is rarely examined in agricultural greenhouse drying.

Fifth, there is a need for more explicit climate-resilience analysis. Warmer and drier conditions may improve drying potential, but smoke transport, dust, variable humidity, and heat stress could undermine operational and environmental performance.

Sixth, smart monitoring and control remain more a conceptual need than a fully documented strength in the uploaded literature set. Future greenhouse dryer research should integrate environmental sensing, predictive control, and adaptive ventilation to balance drying performance with pollution prevention.

CONCLUSION

This updated review confirms that greenhouse drying remains a highly promising pathway for sustainable agricultural processing, but its relevance today extends far beyond simple solar heat utilization. The uploaded source set shows that drying technologies are increasingly evaluated through a more comprehensive sustainability framework that includes energy efficiency, emissions, air quality, residue valorization, occupational exposure, and life-cycle burden.

The literature reviewed here supports five major conclusions. First, drying is still one of the most energy-intensive operations in agricultural and biomass processing, which makes greenhouse drying strategically important as a low-carbon alternative. Second, solar and greenhouse-assisted systems can substantially improve the environmental profile of drying operations, especially when integrated with hybrid heating, heat recovery, and residue-based energy pathways. Third, drying systems can also function as sources or vectors of environmental pollution, including ammonia, ultrafine particles, gaseous pollutants, microplastics, PFAS-associated residues, and noise. Fourth, greenhouse dryers should be treated as integrated environmental systems rather than simple passive thermal enclosures. Fifth, the future of greenhouse drying depends on its ability to combine product quality, pollution prevention, circularity, and intelligent control.

Based on the reviewed evidence, several suggestions are proposed.

1. Future greenhouse dryer studies should include pollution-related variables such as ammonia, particulates, odors, combustion gases, and noise in addition to conventional drying metrics.
2. Designers should prioritize hybrid and climate-responsive greenhouse dryers that combine solar gain with heat recovery, smart ventilation, and low-emission auxiliary energy.
3. Residue-specific drying protocols should be developed for digestate, sludge, food waste, and agricultural by-products to prevent pollution transfer from solid to gaseous phases.
4. More life-cycle assessment studies are needed to compare passive, active, and hybrid greenhouse dryer configurations under realistic operating conditions.
5. Occupational exposure and indoor-like environmental quality issues should be investigated more systematically in active greenhouse drying facilities.
6. Greater attention should be given to the use of greenhouse dryers as circular processing platforms capable of handling crops, residues, and reusable bioresources across seasons.
7. Smart sensing and adaptive control should become central features of next-generation greenhouse dryers so that energy efficiency and environmental pollution control can be optimized simultaneously.

Overall, the literature suggests that the future greenhouse dryer is not merely a solar enclosure. It is a smart, hybrid, circular, and pollution-aware processing platform that can support climate-resilient agriculture and cleaner production if developed with sufficient technical and environmental rigor.

Declaration by Authors

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REFERENCES

1. M. O. Rivett *dkk.*, "Acute health risks to community hand-pumped groundwater supplies following Cyclone Idai flooding," *Sci. Total Environ.*, vol. 806, 2022, doi: 10.1016/j.scitotenv.2021.150598.
2. M. R. Ribeiro *dkk.*, "Amazon Wildfires and Respiratory Health: Impacts during the Forest Fire Season from 2009 to 2019," *Int. J. Environ. Res. Public Health*, vol. 21, no. 6, 2024, doi: 10.3390/ijerph21060675.
3. Y. Zheng *dkk.*, "Assessing the impacts of climate variables on long-term air quality trends in Peninsular Malaysia," *Sci. Total Environ.*, vol. 901, 2023, doi: 10.1016/j.scitotenv.2023.166430.
4. D. F. Martinez-Escobar dan J. Mallela, "Assessing the impacts of phosphate mining on coral reef communities and reef development," *Sci. Total Environ.*, vol. 692, hlm. 1257–1266, 2019, doi: 10.1016/j.scitotenv.2019.07.139.
5. L. Sun, M.-È. Héroux, X. Xu, dan A. J. Wheeler, "Associations between residential fossil fuel combustion and indoor concentrations of nitrogen dioxide, carbon monoxide, and aldehydes in Canadian homes," *J. Expos. Sci. Environ. Epidemiol.*, vol. 35, no. 4, hlm. 649–660, 2025, doi: 10.1038/s41370-025-00762-6.
6. J. Ammendolia, D. Castle, K. Richardson, dan T. R. Walker, "Atmospheric microplastics must be addressed in the global plastics treaty," *Camb. prism., Plast.*, vol. 3, 2025, doi: 10.1017/plc.2025.10004.
7. F. Zhang *dkk.*, "Biofilm-enhanced PFAS removal in constructed wetlands: Sewage sludge biochar drives adsorption and microbial synergy," *Chem. Eng. J.*, vol. 522, 2025, doi: 10.1016/j.cej.2025.167257.
8. Z. Mu *dkk.*, "Chronic drought alters extractable concentrations of mineral elements in Mediterranean forest soils," *Sci. Total Environ.*, vol. 905, 2023, doi: 10.1016/j.scitotenv.2023.167062.
9. T. Ikeda *dkk.*, "Climatic factors in relation to diarrhoea hospital admissions in rural Limpopo, South Africa," *Atmosphere*, vol. 10, no. 9, 2019, doi: 10.3390/atmos10090522.
10. S. Zi *dkk.*, "Co-Transport of Tire Wear Particles with Cd2+ and Ni2+ in Porous Media: Impact of Adsorption Affinity and Desorption Hysteresis," *Water Air Soil Pollut.*, vol. 235, no. 11, 2024, doi: 10.1007/s11270-024-07546-y.
11. M. Variny, D. Jediná, M. Rimár, J. Kizek, dan M. Kšiňanová, "Cutting oxygen production-related greenhouse gas emissions by improved compression heat management in a cryogenic air separation unit," *Int. J. Environ. Res. Public Health*, vol. 18, no. 19, 2021, doi: 10.3390/ijerph181910370.
12. Khalida, V. Arumugam, L. C. Abdullah, L. A. Manaf, dan M. H. Ismail, "Dehydrated Food Waste for Composting: An Overview," *Pertanika J. Sci. Technol.*, vol. 30, no. 4, hlm. 2933–2960, 2022, doi: 10.47836/pjst.30.4.33.
13. Y. Wan, C. Wu, Q. Xue, dan X. Hui, "Effects of plastic contamination on water evaporation and desiccation cracking in soil," *Sci. Total Environ.*, vol. 654, hlm. 576–582, 2019, doi: 10.1016/j.scitotenv.2018.11.123.
14. S. Kim, Y. Park, dan Y. Hwang, "Efficient removal of beta-blockers from water using fluorinated covalent organic polymers: Insights into sigmoidal adsorption behavior and environmental applications," *Environ. Res.*, vol. 285, 2025, doi: 10.1016/j.envres.2025.122439.
15. S. I. Dramé, O. A. Oba, dan N. P. Aydinlik, "Environmental and ecological risk assessment of municipal sewage sludge management using a sustainable solar drying system," *Water Sci. Technol.*, vol. 88, no. 1, hlm. 151–168, 2023, doi: 10.2166/wst.2023.199.
16. M. Hussain, R. N. Malik, dan A. Taylor, "Environmental profile analysis of particleboard production: a study in a Pakistani technological condition," *Int. J. Life Cycle Assess.*, vol. 23, no. 8, hlm. 1542–1561, 2018, doi: 10.1007/s11367-017-1385-9.
17. G. E. Konstantzos, D. Malamis, A. Sotiropoulos, dan M. Loizidou, "Environmental profile of an innovative household biowaste dryer system based on Life Cycle Assessment," *Waste Manage. Res.*, vol. 37, no. 1, hlm. 48–58, 2019, doi: 10.1177/0734242X18792604.

18. K. Munro *dkk.*, “Evaluation of combined sewer overflow impacts on short-term pharmaceutical and illicit drug occurrence in a heavily urbanised tidal river catchment (London, UK),” *Sci. Total Environ.*, vol. 657, hlm. 1099–1111, 2019, doi: 10.1016/j.scitotenv.2018.12.108.
19. W. Lubitz, K. Teeter, E. Parker, R. Dalton, dan J. Dyck, “Experimental Study of Grain Dryer Noise Emissions,” *Environ. - MDPI*, vol. 10, no. 6, 2023, doi: 10.3390/environments10060100.
20. Serra-Compte *dkk.*, “Fluvial biofilms exposed to desiccation and pharmaceutical pollution: New insights using metabolomics,” *Sci. Total Environ.*, vol. 618, hlm. 1382–1388, 2018, doi: 10.1016/j.scitotenv.2017.09.258.
21. E. M. Mollinedo, P. Krecl, A. C. Targino, dan C. I. Moreno R., “From lowland plains to the Altiplano: The impacts of regional transport of wildfire smoke on the air quality of Bolivian cities,” *Atmos. Environ.*, vol. 315, 2023, doi: 10.1016/j.atmosenv.2023.120137.
22. B. Nunes, K. C. Vieira, P. E. R. Pereyra, G. Hallwass, C. V. Cunha, dan R. A. M. Silvano, “‘From the sky to the ground’: fishers’ knowledge, landscape analysis and hydrological data indicate long-term environmental changes in Amazonian clear water rivers,” *Sci. Total Environ.*, vol. 904, 2023, doi: 10.1016/j.scitotenv.2023.166763.
23. N. Giglou, R. Nazari, M. Karimi, M. Lawrence Museru, K. Ntow Opare, dan M. R. Nikoo, “Future eco-hydrological dynamics: Urbanization and climate change effects in a changing landscape: A case study of Birmingham’s river basin,” *J. Clean. Prod.*, vol. 447, 2024, doi: 10.1016/j.jclepro.2024.141320.
24. M. Kim, H. Kim, J. Byun, E. Yang, dan H. Choi, “Gravity-driven removal of tetracycline from water using a hierarchically porous adsorptive nanofibrous membrane system functionalized with metal–organic framework,” *Water Res.*, vol. 290, 2026, doi: 10.1016/j.watres.2025.124939.
25. P. Saetan, P. Phuangbubpha, N. Kaewnok, N. Wanichacheva, S. Suttiruengwong, dan A. Charoenpanich, “Hazard potential of polystyrene and polybutylene succinate microplastics: Cellular toxicity following long-term exposure and Mercury(II) carrier effects,” *Sci. Total Environ.*, vol. 1017, 2026, doi: 10.1016/j.scitotenv.2026.181502.
26. S. Winkler *dkk.*, “Human airway organoids and microplastic fibers: A new exposure model for emerging contaminants,” *Environ. Int.*, vol. 163, 2022, doi: 10.1016/j.envint.2022.107200.
27. Islam, N. Pattnaik, M. M. Moula, T. Rötzer, S. Pauleit, dan M. A. Rahman, “Impact of urban green spaces on air quality: A study of PM10 reduction across diverse climates,” *Sci. Total Environ.*, vol. 955, 2024, doi: 10.1016/j.scitotenv.2024.176770.
28. K. Chojnacka *dkk.*, “Improvements in drying technologies - Efficient solutions for cleaner production with higher energy efficiency and reduced emission,” *J. Clean. Prod.*, vol. 320, 2021, doi: 10.1016/j.jclepro.2021.128706.
29. M. Zhang, Y. Yang, D. Ding, F. Li, dan J. Ma, “Insight into the correlation between swelling performance and U(VI) sorption ability of humic-like substances based hydrogel,” *J. Environ. Chem. Eng.*, vol. 13, no. 4, 2025, doi: 10.1016/j.jece.2025.117300.
30. W. Berg, R. Salamat, H. Scaar, dan J. Mellmann, “Investigation of nitrogen loss during laboratory scale fixed-bed drying of digestate,” *Waste Manage.*, vol. 129, hlm. 26–34, 2021, doi: 10.1016/j.wasman.2021.05.003.
31. Z. Chen, V. Kamchoom, dan R. Chen, “Landfill gas emission through compacted clay considering effects of crack pathway and intensity,” *Waste Manage.*, vol. 143, hlm. 215–222, 2022, doi: 10.1016/j.wasman.2022.02.032.
32. P. G. Ponnusamy dan S. Mani, “Life cycle assessment of manufacturing cellulose nanofibril-reinforced chitosan composite films for packaging applications,” *Int. J. Life Cycle Assess.*, vol. 27, no. 3, hlm. 380–394, 2022, doi: 10.1007/s11367-022-02035-y.
33. Quispe, R. Navia, dan R. Kahhat, “Life Cycle Assessment of rice husk as an energy source. A Peruvian case study,” *J. Clean. Prod.*, vol. 209, hlm. 1235–1244, 2019, doi: 10.1016/j.jclepro.2018.10.312.
34. H. Yang *dkk.*, “Mercury Pollution History in Tropical and Subtropical American Lakes: Multiple Impacts and the Possible Relationship with Climate Change,” *Environ. Sci. Technol.*, vol. 57, no. 9, hlm.

3680–3690, 2023, doi: 10.1021/acs.est.2c09870.

35. Z. Jing *dkk.*, "Modeling optimization and application of modified drinking water sludge for high-efficiency phosphorus removal," *J. Environ. Manage.*, vol. 394, 2025, doi: 10.1016/j.jenvman.2025.127259.
36. J. L. Vallejo-García *dkk.*, "Multifunctional smart polymers and citizen science for a comprehensive approach to nitrate pollution: Curative and preventive strategies," *Environ. Technol. Innov.*, vol. 40, 2025, doi: 10.1016/j.eti.2025.104595.
37. G. Weber, U. Honecker, dan J. Kubiniok, "Nitrate dynamics in springs and headwater streams with agricultural catchments in southwestern Germany," *Sci. Total Environ.*, vol. 722, 2020, doi: 10.1016/j.scitotenv.2020.137858.
38. M. Fernández-Martínez, J. Corbera, X. Domene, F. Sayol, F. Sabater, dan C. Preece, "Nitrate pollution reduces bryophyte diversity in Mediterranean springs," *Sci. Total Environ.*, vol. 705, 2020, doi: 10.1016/j.scitotenv.2019.135823.
39. T.-C. Le, C. Liu, C.-S. Tang, X.-Y. Zhang, dan B. Shi, "Numerical Simulation of Desiccation Cracking in Clayey Soil Using a Multifield Coupling Discrete-Element Model," *J. Geotech. Geoenviron. Eng.*, vol. 148, no. 2, 2022, doi: 10.1061/(ASCE)GT.1943-5606.0002747.
40. G. H. El-Sherif, "OCCUPATIONAL AND ENVIRONMENTAL HEALTH PROBLEMS RELATED TO CLIMATE CHANGE IN EGYPT (REVIEW ARTICLE)," *Egypt. J. Occup. Med.*, vol. 49, no. 2, hlm. 1–16, 2025, doi: 10.21608/ejom.2025.371549.1366.
41. D. S. B. Ortega, V. Roveri, M. D. S. Paço, D. T. Lebre, L. A. Maranho, dan C. D. S. Pereira, "Occurrence and potential ecological risks of pharmaceuticals and illicit drugs (PhIDs) in the Santos-São Vicente Estuarine System (SSVES), Brazil," *Mar. Pollut. Bull.*, vol. 219, 2025, doi: 10.1016/j.marpolbul.2025.118291.
42. F. Chamorro, N. G. Chate Galvis, E. M. Combatt, dan M. Palencia, "Oxidized Cassava Starch, a Sustainable Material for Rapid Ammonium Adsorption and Controlled Release," *J. Polym. Environ.*, vol. 34, no. 2, 2026, doi: 10.1007/s10924-025-03746-7.
43. M. A. Eichler *dkk.*, "Partitioning of Neutral PFAS in Homes and Release to the Outdoor Environment: Results from the IPA Campaign," *Environ. Sci. Technol.*, vol. 58, no. 42, hlm. 18870–18880, 2024, doi: 10.1021/acs.est.4c05286.
44. Z. Li, "PBCLM: A top-down causal modeling framework for soil standards and global sustainable agriculture," *Environ. Pollut.*, vol. 263, 2020, doi: 10.1016/j.envpol.2020.114404.
45. S. Royano, A. de la Torre, I. Navarro, dan M. Á. Martínez, "Pharmaceutically active compounds (PhACs) in surface water: Occurrence, trends and risk assessment in the Tagus River Basin (Spain)," *Sci. Total Environ.*, vol. 905, 2023, doi: 10.1016/j.scitotenv.2023.167422.
46. V. Lavor, J. Wei, O. Coceal, S. Grimmond, dan Z. Luo, "Quanta emission rate during speaking and coughing mediated by indoor temperature and humidity," *Environ. Int.*, vol. 198, 2025, doi: 10.1016/j.envint.2025.109379.
47. M. Amin *dkk.*, "Seasonal anomaly of particulate matter concentration in an equatorial climate: Evaluating the transboundary impact from neighboring provinces on Padang City, Indonesia," *Environ. Monit. Assess.*, vol. 196, no. 11, 2024, doi: 10.1007/s10661-024-13160-6.
48. N. M. Koch *dkk.*, "Selecting lichen functional traits as ecological indicators of the effects of urban environment," *Sci. Total Environ.*, vol. 654, hlm. 705–713, 2019, doi: 10.1016/j.scitotenv.2018.11.107.
49. S.-G. Jeong, L. Wallace, dan D. Rim, "Size-resolved emission rates of episodic indoor sources and ultrafine particle dynamics," *Environ. Pollut.*, vol. 338, 2023, doi: 10.1016/j.envpol.2023.122680.
50. M. Mnguni, S. Hobongwana, dan P. N. Nomngongo, "Sub-100 nm resorcinol-formaldehyde hollow spheres to remove heavy metals from water," *npj Clean Water*, vol. 9, no. 1, 2026, doi: 10.1038/s41545-025-00552-5.
51. P. Wang, R. Duan, Y. Li, M. Yan, H. Han, dan Y. Sun, "Sustainable Fluoride Remediation: Unlocking the Potential of Modified Oyster Shells Through Calcination and Phosphoric Acid Treatment," *Water Environ. Res.*, vol. 97, no. 6, 2025, doi: 10.1002/wer.70102.

52. N. Amir, F. Hussin, M. K. Aroua, dan M. Gozan, "Sustainable valorization of seaweed industrial by-product: Converting filter cake into valuable resources," *J. Environ. Manage.*, vol. 382, 2025, doi: 10.1016/j.jenvman.2025.125342.
53. Hudon, M. Jean, dan G. Létourneau, "Temporal (1970–2016) changes in human pressures and wetland response in the St. Lawrence River (Québec, Canada)," *Sci. Total Environ.*, vol. 643, hlm. 1137–1151, 2018, doi: 10.1016/j.scitotenv.2018.06.080.
54. G. Z. Macher, "The Impact of Rainwater Quality Harvested from Asbestos Cement Roofs on Leaf Temperature in Solanum lycopersicum as a Plant Water Stress Indicator," *Water*, vol. 17, no. 14, 2025, doi: 10.3390/w17142070.
55. Hossein Mardi *dkk.*, "The Lake Urmia environmental disaster in Iran: A look at aerosol pollution," *Sci. Total Environ.*, vol. 633, hlm. 42–49, 2018, doi: 10.1016/j.scitotenv.2018.03.148.
56. T. B. Hennig *dkk.*, "Toxicity of fipronil to Folsomia candida in contrasting tropical soils and soil moisture contents: effects on the reproduction and growth," *Ecotoxicology*, vol. 31, no. 1, hlm. 64–74, 2022, doi: 10.1007/s10646-021-02490-7.
57. M. N. González-Alcaraz, S. Loureiro, dan C. A. M. van Gestel, "Toxicokinetics of Zn and Cd in the earthworm Eisenia andrei exposed to metal-contaminated soils under different combinations of air temperature and soil moisture content," *Chemosphere*, vol. 197, hlm. 26–32, 2018, doi: 10.1016/j.chemosphere.2018.01.019.
58. Y. Hao *dkk.*, "Transported smoke from crop residue burning as the major source of organic aerosol and health risks in northern Indian cities during post-monsoon," *Environ. Int.*, vol. 202, 2025, doi: 10.1016/j.envint.2025.109583.
59. T. Adeleye, M. M. Bahar, M. Megharaj, dan M. M. Rahman, "Upcycling Microplastic-Laden Spent Adsorbents to Mitigate Secondary Pollution: Insights into the Drivers, Pressures, State, Impacts, Responses (DPSIR) Framework," *Water*, vol. 18, no. 4, 2026, doi: 10.3390/w18040461.
60. K. Warner, N. F. Sonti, E. M. Cook, R. A. Hallett, L. R. Hutyra, dan A. B. Reinmann, "Urbanization exacerbates climate sensitivity of eastern United States broadleaf trees," *Ecol. Appl.*, vol. 34, no. 4, 2024, doi: 10.1002/eap.2970.
61. N. S. Domingues, É. L. Romão, D. S. Alvim, J. P. Marques, V. G. S. Rodrigues, dan M. C. Kasemodel, "Use of Construction and Demolition Waste for the Treatment of Dye-Contaminated Water Toward Circular economy," *Water Air Soil Pollut.*, vol. 235, no. 10, 2024, doi: 10.1007/s11270-024-07421-w.
62. Z.-L. Zhao, W.-W. Li, F. Wang, dan Y.-Q. Zhang, "Using of hydrated lime water as a novel degumming agent of silk and sericin recycling from wastewater," *J. Clean. Prod.*, vol. 172, hlm. 2090–2096, 2018, doi: 10.1016/j.jclepro.2017.11.213.
63. W. Ouyang, X. Wan, Y. Xu, X. Wang, dan C. Lin, "Vertical difference of climate change impacts on vegetation at temporal-spatial scales in the upper stream of the Mekong River Basin," *Sci. Total Environ.*, vol. 701, 2020, doi: 10.1016/j.scitotenv.2019.134782.
64. F. Kordbacheh, D. N. Flaten, dan R. H. Gulden, "Weed community dynamics under repeated fertilization with different nutrient sources over 5 years," *Agric. Ecosyst. Environ.*, vol. 346, 2023, doi: 10.1016/j.agee.2022.108328.
65. Quishpe-Vásquez, P. Oliva, E. A. López-Barrera, dan A. Casallas, "Wildfires impact on PM2.5 concentration in galicia Spain," *J. Environ. Manage.*, vol. 367, 2024, doi: 10.1016/j.jenvman.2024.122093.

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