



Photocatalytic Treatment Technology for Reducing Chemical Contaminants in Fruit Processing

Amar Jensi Solanki

SBN Govt P G College

Barwani MP 451551



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Abstract : Chemical contamination in fruit processing presents challenges involving pesticide residues, contaminated washing water and mycotoxins in processed products. Photocatalytic treatment offers a potential approach through light-driven reactions that transform susceptible contaminants. However, performance depends on the pollutant, treatment matrix, catalyst and irradiation conditions. This paper evaluates photocatalytic technology through a focused narrative review of twelve verified publications addressing semiconductor mechanisms, water-treatment engineering, pesticide removal and fruit-related applications. Published numerical findings were extracted without combining incompatible experiments. A study of nitrogen-doped chitosan-titanium dioxide reported complete degradation of patulin initially present at 500 µg/kg in apple juice within 35 minutes. Supported titanium dioxide research investigated citrus-processing pesticides at 100 µg/L each and demonstrated substantial matrix-dependent behavior. Fresh-produce research reported pesticide-removal ranges of 72–94% for combined ultraviolet treatments, compared with 53–73% for bubble-water washing; nevertheless, adding titanium dioxide did not significantly improve

pesticide removal relative to combined ultraviolet treatment alone. These findings indicate that contaminant disappearance, mineralization, detoxification and product acceptability must be assessed separately. Photocatalysis appears promising for selected processing-water and juice applications, but its contribution must be demonstrated against appropriate controls. Commercial development requires verified analytical methods, transformation-product assessment, catalyst containment, energy evaluation and validation under realistic processing conditions.

Keywords: photocatalysis; fruit processing; pesticide residues; patulin; titanium dioxide; advanced oxidation; processing water.

Introduction

Fruit processing involves several opportunities for chemical contaminants to enter, persist or move between product and water streams. Agricultural and postharvest treatments can leave pesticide residues, while fungal deterioration can introduce mycotoxins into susceptible products. Washing may remove part of a surface residue, but removal from fruit can transfer



contamination into the washing medium rather than destroy it.

Conventional washing also has limitations where residues have penetrated the fruit surface. Yang et al. (2017) demonstrated that surface and internalized pesticide residues require separate consideration when evaluating apple washing. Their findings establish an important starting point: a treatment that cleans the surface cannot automatically be assumed to eliminate contamination within fruit tissues. [PubMed](#)

Photocatalysis is investigated as a means of transforming contaminants through reactions initiated by light interacting with a suitable catalyst. Titanium dioxide, or TiO_2 , is extensively studied, although modified catalysts and assisted oxidation systems are also used. Its effectiveness depends on photochemical activity, pollutant accessibility and reactor conditions. Foundational reviews explain the relationship between semiconductor excitation, interfacial reactions and environmental applications. [ACS Publications](#)

For fruit processing, three applications must be distinguished: treating contaminated process water, treating residues on produce surfaces and treating contaminants within products such as juice. Each has different requirements for light penetration, catalyst separation, analytical verification and product-quality protection.

Research Problem

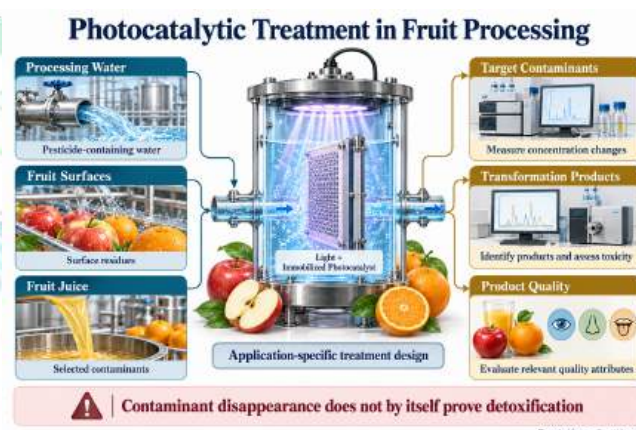
Photocatalytic studies frequently demonstrate contaminant reduction under controlled conditions, but translating these results into fruit-processing practice remains difficult. Aqueous model solutions are less complex than washing water containing dissolved organic matter, suspended solids and multiple contaminants. Fruit surfaces introduce additional limitations through uneven geometry, shadowing and restricted contact.

Another problem concerns the meaning of “removal.” A lower measured concentration may result from adsorption, transfer into another phase, direct photolysis or photocatalytic transformation. Even genuine transformation does not establish complete mineralization or reduced toxicity.

The research problem is therefore to determine which applications are supported by published evidence and which methodological requirements are necessary for reliable claims about chemical-contaminant reduction.

Objectives

The paper examines photocatalytic mechanisms relevant to fruit processing, reviews verified application studies and compares selected published numerical findings. It also identifies suitable controls, analytical endpoints and operational considerations for future experimental validation.



Research Questions

The analysis addresses whether photocatalysis offers an identifiable advantage over washing or irradiation alone; how processing matrices affect treatment performance; and which measurements are required to distinguish contaminant disappearance from a meaningful improvement in chemical safety.

Literature Review

Semiconductor Mechanisms and Treatment Engineering

Hoffmann et al. (1995) established a foundational account of semiconductor photocatalysis for environmental treatment. Their review provides the basis for understanding light-induced charge generation and reactions at catalyst interfaces. It supports investigation of contaminant transformation, while



offering no justification for assuming that every pollutant will be efficiently treated. [ACS Publications](#)

Schneider et al. (2014) examined TiO₂ photocatalysis through its mechanisms and material characteristics. Their contribution emphasizes that catalyst performance depends on more than material identity. Charge behavior, surface properties and material structure are relevant when interpreting claims about improved photocatalytic activity. [ACS Publications](#)

Chong et al. (2010) reviewed water-treatment development from catalyst and photoreactor design to process optimization and kinetics. This engineering perspective is important because a material exhibiting laboratory activity may perform differently when deployed in a larger reactor with different irradiation and transport conditions. [ScienceDirect](#)

Malato et al. (2009) discussed solar photocatalysis for water decontamination and disinfection. Their review situates solar treatment within reactor development and wastewater management. It supports investigation of processing-water applications while highlighting the need to evaluate the complete treatment system. [ScienceDirect](#)

Ahmed et al. (2011) reviewed operating parameters influencing heterogeneous photocatalytic degradation of pesticides and phenolic contaminants. Their analysis reinforces the importance of conditions such as catalyst loading, pH and irradiation. Consequently, degradation percentages should always be reported with their experimental context. [ScienceDirect](#)

Pesticides and Transformation Products

Calza et al. (2003) investigated thiabendazole phototransformation products using ion-trap tandem mass spectrometry. This work is relevant because parent-compound analysis alone cannot describe the chemical composition of treated water. Transformation-product identification should accompany degradation claims where possible. [pubmed.ncbi.nlm.nih.gov](#)

Jiménez et al. (2015) studied supported TiO₂ in a solar reactor for pesticides associated with citrus-processing wastewater. Their findings demonstrate that both pollutant identity and water matrix influence

performance. Supported catalysts also offer a route for examining repeated use without relying exclusively on suspended powders. [Wiley Online Library](#)

Jiménez-Tototzintle et al. (2015) evaluated real agro-food wastewater using biological treatment followed by supported TiO₂/H₂O₂ solar photocatalysis. The study supports examining photocatalysis as part of a treatment train, rather than expecting it to perform every function required for complex industrial effluent. [hero.epa.gov](#)

Aliste et al. (2020) investigated solar-driven treatment of pesticides in leaching water. Most compounds responded more readily than flonicamid, illustrating pollutant-specific limitations. This evidence is relevant to water-treatment design but should not be presented as a direct fruit-surface experiment. [pubmed.ncbi.nlm.nih.gov](#)

Produce and Juice Applications

Yang et al. (2017) compared commercial and household washing agents for pesticide residues on and within apples. Although the study did not evaluate photocatalysis, it supplies a necessary comparator perspective: residue location and penetration affect the achievable effectiveness of surface treatment. [ACS Publications](#)

Choi et al. (2020) compared ultraviolet photolysis and TiO₂-assisted treatment in aqueous solutions and on fresh-cut carrots. Their study provides useful fresh-produce evidence, but carrots are vegetables and the results are not direct proof of effectiveness on fruit. Importantly, irradiation controls allowed the additional contribution of the catalyst to be assessed. [United Arab Emirates University](#)

Huang and Peng (2021) investigated a nitrogen-doped chitosan–TiO₂ nanocomposite for patulin degradation in apple juice. This is directly relevant to a processed fruit matrix. The study examined photocatalytic activity alongside selected juice-quality characteristics, providing a broader assessment than contaminant concentration alone. [agris.fao.org](#)

Research Gap



The literature establishes scientific feasibility for selected applications but does not demonstrate a universally effective fruit-processing treatment. Evidence is uneven across products, contaminants and operating scales.

Important gaps include direct comparisons with irradiation alone, adequate distinction between adsorption and degradation, transformation-product characterization and independent confirmation of detoxification. Continuous operation, catalyst loss and variability in processing-water composition also require further assessment.

A useful research framework must therefore connect chemical analysis, process engineering and product-quality evaluation.

Scientific Framework

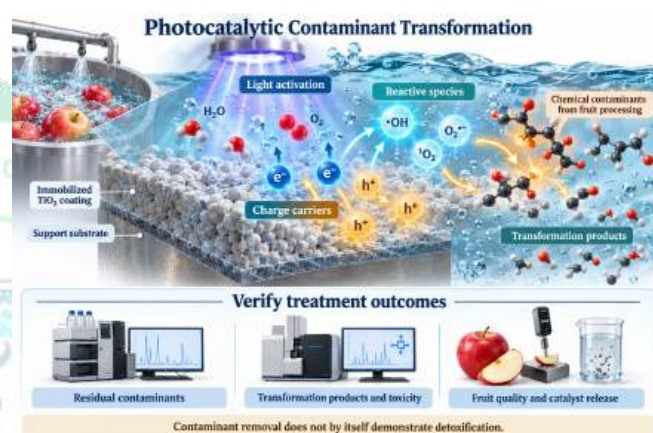
In semiconductor photocatalysis, absorption of suitable light can generate excited electrons and associated holes. Their subsequent reactions depend on the catalyst, surrounding medium and available reactants. Charge recombination competes with useful interfacial reactions, so increased illumination or catalyst addition does not necessarily produce proportional improvements. [ACS Publications](#)

For this paper, treatment performance is interpreted through four distinct endpoints.

Endpoint	Meaning	Required evidence
Parent-compound removal	Reduction in measured target concentration	Validated target analysis
Chemical transformation	Formation of different chemical species	Transformation-product analysis
Mineralization	Conversion of organic carbon toward	Appropriate carbon measurements and balance

	inorganic forms	
Detoxification	Reduction in relevant biological effects	Suitable toxicity assessment

Product acceptability forms a separate endpoint. A chemically effective treatment may still be unsuitable if it adversely affects flavor, color or composition.



Materials and Methods

Study Design

A focused narrative review with descriptive evidence extraction was conducted. No original reactor experiment, fruit treatment or laboratory measurement was performed. Accordingly, the results concern published findings and their interpretation.

Literature Identification

Search terms combined “photocatalysis,” “fruit processing,” “pesticide degradation,” “citrus wastewater,” “apple juice,” “patulin,” “TiO₂” and “transformation products.” Publication identities and bibliographic details were verified through publisher records, institutional repositories and recognized bibliographic databases.

Twelve publications were selected to cover foundational mechanisms, reactor engineering and relevant application studies. The search was targeted rather than

exhaustive; no systematic screening total or comprehensive coverage claim is made.

Evidence Selection and Extraction

Application studies were evaluated according to their actual treatment matrix. Results from model water, industrial effluent, produce surfaces and apple juice were retained separately.

Extracted item	Purpose
Matrix and product	Establishes where the treatment was tested
Target contaminant	Prevents generalization across different chemicals
Initial concentration	Provides context for reported degradation
Catalyst and light source	Identifies the treatment configuration
Exposure conditions	Defines the observation period and irradiation context
Comparator	Separates catalyst activity from washing or photolysis
Analytical endpoint	Distinguishes disappearance from broader treatment outcomes
Statistical interpretation	Preserves reported significance without inventing tests

Quantitative Interpretation



Reported percentages, concentrations and durations were reproduced with source attribution. Removal ranges were not converted into pooled means because they represented different contaminants or treatment configurations.

For future primary studies, removal efficiency can be calculated as:

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100$$

Here, C_0 and C_t are concentrations before and after treatment. This calculation describes concentration reduction; it does not identify the mechanism responsible.

A pseudo-first-order model may be examined using:

$$\ln(C_0/C_t) = k_{app}t$$

However, the model must be justified by actual time-series data. No rate constant was calculated from a reported “complete degradation” endpoint, because a zero or below-detection result cannot support an unqualified logarithmic calculation.

Results

Application-Specific Evidence

The selected studies support different roles for photocatalytic technology.



Application	Relevant evidence	Interpretation
Citrus-processing water	Supported TiO ₂ solar treatment	Matrix-sensitive pesticide transformation
Agro-food effluent	Biological treatment followed by photocatalysis	Potential tertiary-treatment role
Apple juice	Modified TiO ₂ treatment of patulin	Direct processed-fruit application
Produce surfaces	UV and TiO ₂ comparisons on carrots	Transferable experimental design, requiring fruit validation
Leaching water	Solar treatment of multiple pesticides	Evidence of contaminant-specific resistance

Choi et al.: fresh-cut carrots	Bubble-water washing	53–73% pesticide removal	Vegetable-surface evidence
Choi et al.: fresh-cut carrots	Combined UV treatment configurations	72–94% pesticide removal	No significant advantage from adding TiO ₂ to combined UV
Aliste et al.: leaching water	Flonicamid under solar exposure	Approximately 20% degradation after 240 minutes	Resistant response under the tested conditions

Sources: Huang and Peng (2021), Jiménez et al. (2015), Choi et al. (2020) and Aliste et al. (2020). The table contains published values rather than a newly generated dataset. agris.fao.org

This separation prevents wastewater findings from being represented as demonstrated reductions in edible fruit.

The findings demonstrate substantial heterogeneity. A rapid response in one juice–contaminant system cannot predict treatment duration for pesticides in another matrix.

Published Quantitative Findings

Study and matrix	Published measurement	Reported outcome	Interpretive boundary
Huang and Peng: apple juice	Initial patulin: 500 µg/kg	Complete degradation reported within 35 minutes	Does not independently establish complete mineralization
Jiménez et al.: water matrices	Thiabendazole, imazalil and acetamiprid: 100 µg/L each	Complete imazalil degradation; matrix effects for other targets	Results depend on pollutant and water composition

Statistical Interpretation

The strongest comparative lesson concerns the need for irradiation controls. Choi et al. reported no significant difference in pesticide-removal efficiency between combined UV and combined UV–TiO₂ treatments. The higher removal range relative to washing therefore cannot be attributed exclusively to photocatalysis.

Ranges across chemicals are also not confidence intervals. Their endpoints cannot be subtracted to obtain a matched treatment effect, nor can they establish an average improvement without compound-level data.

Product-Quality Assessment

Huang and Peng reported limited effects on selected apple-juice characteristics, including reducing sugar,



pH, titratable acidity and soluble solids. These observations support continued product-focused investigation. They do not establish unchanged sensory quality, complete nutritional equivalence or suitability under every juice-processing condition. agris.fao.org

Discussion

Processing-Water Treatment

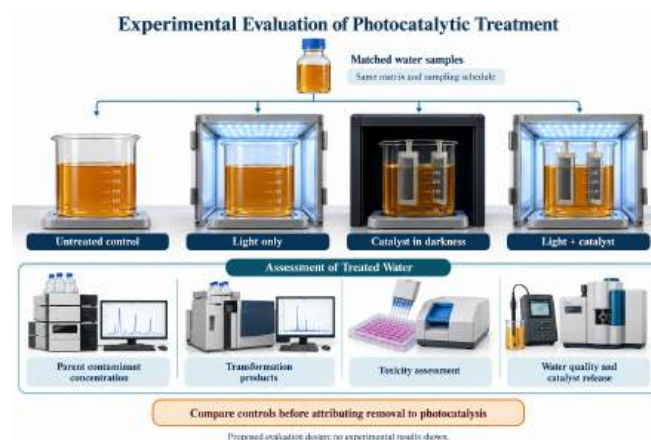
An operationally plausible application is treatment of a separated water stream. This allows irradiation, catalyst retention and monitoring to occur in a dedicated reactor. Nevertheless, water intended for reuse requires assessment against its intended function; target-pesticide reduction alone cannot establish overall suitability.

The agro-food treatment-train evidence supports investigating pretreatment followed by photocatalytic polishing. Reducing matrix complexity before irradiation may be useful, but performance must be measured with representative effluent rather than inferred from clean-water experiments.

Direct Product Treatment

Juice treatment presents different constraints. Light distribution, product composition and catalyst separation become central. Product-compatible conditions must preserve acceptable quality while achieving a verified chemical endpoint.

For whole fruit, contamination within tissues may be less accessible than surface residues. The apple-washing evidence provides a reason to measure surface, peel and internal fractions where appropriate. A surface-treatment result should not be described as total-fruit decontamination without such verification.



Controls and Causal Attribution

A reliable experiment should include untreated samples, dark catalyst controls, irradiation without catalyst and irradiation with catalyst. Where an added oxidant is used, its independent contribution also requires assessment.

Dark controls identify adsorption-related losses. Irradiation-only controls identify direct photolysis. Measurement of fruit and water fractions helps distinguish destruction from physical transfer. Independent reactor runs, rather than repeated injections from one sample, should provide the basis for treatment replication.

Analytical and Statistical Requirements

Target analysis should report recovery, detection and quantification limits, calibration and matrix effects. Samples must be collected and handled consistently so treatment does not continue unintentionally after sampling.

Repeated sampling from one reactor requires an analysis that recognizes within-run dependence. Treatment and exposure time may be modeled jointly, while contaminant identity should remain explicit. Means, variability, effect sizes and exact statistical comparisons should be reported from actual data.

“Complete removal” should be accompanied by an analytical limit. Below-detection findings should not be converted into exact zero concentrations or used to assert complete detoxification.



Practical Implications

Photocatalytic equipment must be evaluated for throughput, irradiation delivery, maintenance, catalyst durability and energy demand. Supported catalysts can simplify separation, but their retention and long-term activity require verification. Suspended catalysts require a dependable recovery step.

A commercially useful evaluation should report treatment effectiveness together with operating cost and product-quality outcomes. Solar systems additionally require characterization of changing irradiation conditions. Treatment time alone is insufficient for comparing systems exposed to different light intensities.

Limitations

The paper uses a targeted literature selection and does not provide a meta-analysis. Some studies were accessible through abstracts or institutional records, limiting extraction of full methodological detail.

The numerical findings originate from different matrices and cannot be pooled as a single estimate of fruit-processing effectiveness. The carrot study is supporting produce evidence, and the leaching-water study is supporting water-treatment evidence.

Conclusion

Photocatalytic treatment has credible potential for reducing selected chemical contaminants associated with fruit processing. Evidence is particularly relevant to processing-water treatment and a demonstrated apple-juice application. However, performance is pollutant-specific, matrix-sensitive and dependent on reactor conditions.

Reliable adoption requires proof of the catalyst's additional contribution, validated contaminant analysis, assessment of transformation products and protection of product quality. Parent-compound disappearance is an important measurement, but it must be interpreted alongside mineralization, toxicity and operational performance.

Declarations

Data availability: All numerical findings originate from the cited publications. No original experimental dataset was generated.

Ethics: No new human or animal experiments were conducted.

Funding and competing interests: These declarations must reflect the submitting authors' actual circumstances.

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