Ensuring safety in soy:
A review of chlorpyrifos detection and mitigation for consumer confidence

by

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Abstract

With growing consumer interest in food production and processing, understanding how agricultural practices balance profitability with food safety is crucial. The agricultural industry utilizes various methods to ensure crop success, including pesticide use. Chlorpyrifos (CPF), a widely used pesticide, remains under regulatory scrutiny due to concerns about its safety and environmental impact. After alternating between federal approvals and restrictions, the United States (U.S.) Environmental Protection Agency (EPA) authorized CPF for use on soybeans in February 2024. This shifting regulatory stance highlights the need to accurately identify CPF residues on soybeans and evaluate both natural and processing mitigation factors to reduce their presence. This report evaluates the efficacy of removing chlorpyrifos by naturally occurring environmental factors, such as storage time and sunlight exposure, as well as interventive processes—washing with water, ultrasound (ULS), ozone (O_3), heat application, and cold plasma treatment—on the food safety of soybeans. Additionally, the importance of a multi-step approach is emphasized for effectively reducing CPF residues, as storage or heat processing alone often do not meet safety thresholds. Cold plasma (CP) resulted in surface damage to the beans, rendering the process unacceptable, although faster to reach tolerance levels than O_3. While washing and O_3 treatments demonstrated moderate success, a combination of ULS and O_3 treatments demonstrated synergistic effects in reducing CPF concentrations on soybeans.

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The journey of completing this master's degree in food science resulted in a personal and professional transformation. Over these four years, often one class per semester at a time, my perspective shifted, my children grew from infancy and pre-school to elementary school, and technology continued to reshape how we learn and work. I am grateful for the influences in my life that allowed me to prioritize adaptability, growth, and lifelong learning.

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Thank you to the North Dakota State University Extension team and the many mentors who influenced my academic and professional path, including Jim Gray's guidance regarding chemical analyses. I also appreciate the U.S. Department of Veterans Affairs medical professionals whose dedication to my health enables me to pursue this opportunity. This achievement is not mine alone but a reflection of the incredible support system around me.

V. Literature Review

A. Background Information on Chlorpyrifos

1. Classification, Properties, and Mechanism of Action

Pesticides are chemical or biological agents designed to deter, incapacitate, or eliminate pests, encompassing a broad spectrum of compounds targeting insects, plants, rodents, or fungi (Rahman et al., 2021). Rahman et al (2024) explained that these agents are categorized based on their specificity: broad-spectrum pesticides affect a wide array of pests, whereas narrow-spectrum pesticides are tailored to specific species. Chlorpyrifos (CPF) is a broad-spectrum organophosphate classified as an insecticide, acaricide, and miticide (EPA, 2011). First registered for use in the U.S. by the Environmental Protection Agency (EPA) in 1965, CPF is extensively utilized in agriculture to manage soil-borne insects and foliar pests across various crops, fruits, and vegetables (EPA, 2011). Its application necessitates proper training and strict adherence to federal guidelines to mitigate adverse impacts on human health and the environment, as overseen in the U.S. by the EPA (EPA, 2011). Commercially, CPF has marketing labels under numerous trade names, including Dursban, Lorsban, Cobalt, Brodan, Lock-on, Hatchet, Nufos, Tricel, Warhawk, Detmol UA, Dowco 179, Dursban, Empire, Eradex, Lorsban, Paqeant, Piridane, Scout, and Stipend (National Pesticide Information Center, 2023). Chemically, CPF is identified as O,O-diethyl-O-(3,5,6-trichloro-2-pyridyl)-phosphorothioate, with the molecular formula $C_9H_{11}Cl_3NO_3PS$ (EPA, 2000).

CPF is a white-to-tan crystalline solid classified as a synthetic organophosphate pesticide (OP) commonly used worldwide (Sud & Kaur, 2011). Sud and Kaur (2011) explained that CPF has a defining ester group that binds to acetylcholinesterase (AChE) in pests, which stops nerve function. CPF functions by inhibiting AChE, an enzyme crucial for nerve function, leading to the accumulation of acetylcholine in the synaptic cleft between neurons (Sud & Kaur, 2011). Normally, AChE breaks down acetylcholine (ACh) after it transmits a nerve signal, allowing neurons to reset for the next signal. However, when CPF inhibits AChE, acetylcholine builds up in the synaptic cleft, leading to the overstimulation of nerve receptors (Sud & Kaur, 2011). This excessive nerve signaling can cause neurotoxicity, paralysis, and, ultimately, death in pests (Sud & Kaur, 2011).

Esters can break down in the environment, so CPF does not last forever (ATSDR, 1997). The half-life of CPF, the time necessary for one-half of the original amount of the pesticide to degrade, ranges from 10 to 120 (d and varies depending on the surrounding environment (Foong et al., 2020). CPF is hydrophobic, poorly soluble in water, and more stable in neutral and less acidic environments (Anbarasan et al., 2022). When exposed to water, sunlight, or enzymes, the ester bond in CPF can break, turning it into a less toxic form, such as in the soil, 3,5,6-trichloro-2-pyridinol (TCP), or inactive forms (EPA, 2020). Since esters are easy to break, CPF can transform into toxic byproducts like CPF oxon, which still affects AChE (EPA, 2020). Even small residues can break down in the liver and potentially harm human brain development such as in unborn children (ATSDR, 1997). Given the potential health risks associated with CPF, including its neurotoxic effects and the possibility of adverse developmental outcomes, its use continues to receive increased scrutiny and regulatory actions.

2. Use in Soybean Production

Soybeans (*Glycine max*) are in high demand as a source of plant-based protein for human and animal diets due to their high protein (40-42%) and oil content (18-22%) (Anbarasan et al., 2022). Soybeans and their products, such as soybean meal for animal feed and soybean oil for human consumption, are the most globally traded agricultural commodity, accounting for just under nine percent of the total value of global agricultural trade (Valdes et al., 2023). Soybean meal (soybean cake) is the dry matter resulting from crushing or the extraction process used to separate the oil from the seed leaving a low-fat, dry product (Valdes et al., 2023).

Soybeans originated in China, where beans are still cultivated today, along with the U.S., Brazil, Argentina, and India, contributing 90 percent or 335 million metric tons in 2016, of the total soybean production worldwide (Anbarasan et al., 2022). In the 2021 to 2022 market, Brazil became the world's largest soybean exporter, supplying 77.1 million metric tons of soybeans, followed by the U.S. exporting 53.3 million metric tons (Valdes et al., 2023). China's increasing demand stimulated this growth in Brazil's soybean exports from 5.7 million metric tons in 2004 to 60.5 million metric tons in 2021 (Valdes et al., 2023). To meet market demands, soybeans are often grown and cultivated using pesticides, including CPF as an insecticide (Valdes et al., 2023). The global pesticide consumption in 2019 was approximately 4.19 million metric tons (Pathak et al., 2022). China was by far the largest pesticide-using country at 1.76 million metric

tons, followed by the U.S. at 370 thousand metric tons, and Brazil using 342 thousand metric tons (Pathak et al., 2022). CPF usage is estimated in China to be about 2,000 metric tons per year during the last decade, and Brazil usage reached 798,000 metric tons (using a density of 1.4 kg/L for CPF) specifically on soybeans (Anbarasan et al., 2022). The EPA estimates that approximately 2,313 metric tons of CPF from 2014-2018 were used annually, with the most used on soybeans and alfalfa crops at a rate of 454 metric tons applied annually to each crop in the U.S. (EPA, 2025).

B. Government Oversight of Chlorpyrifos

Regulatory changes for the controlled use of CPF in the U.S. continue, including bans, reinstatements, and ongoing reviews due to legal and administrative decisions since 2000 (EPA, 2025). In 1996, the Food Quality Protection Act (FQPA) set a more stringent safety standard to especially protect children (EPA, 2025). After finalizing the CPF risk assessments for re-registration, which occurs every 15 years, the EPA identified the need to modify certain CPF uses to meet the revised safety standard and address human health and environmental risks from CPF exposure (EPA, 2025). In 2000, science-based research provided enough evidence to discontinue all CPF use in the U.S. on tomatoes, restricting use on apples to pre-bloom and dormant application timing, and lowering the grape tolerance to solely a dormant application (EPA, 2000). This means CPF is sprayed on dormant leafless plants or before budding occurs (EPA, 2000). Residential use was also banned in 2000 by the EPA (EPA, 2000).

In 2002, label changes to ensure environmental and worker safety were implemented based on the 2006 registration eligibility decision for CPF involving a human health risk assessment (EPA, 2025). In 2012, the EPA lowered the aerial pesticide application rates and created “no-spray” buffer zones for set application methods to protect children and bystanders in places where people would be at risk (EPA, 2025). A revised human health risk assessment for all CPF uses occurred in 2014, involving results from the first risk assessment from 2011, the 2012 spray drift exposure study, and public comment (EPA, 2025). Those results were published in 2016, along with the issuance of the proposed rule retaining the 10 times FQPA safety factor (EPA, 2025). There were several assessments issued by the EPA in 2020 about CPF including an ecological risk assessment, a third revision to the human health risk assessment, and an updated CPF drinking water assessment for registration resulting in a proposed interim decision also

supporting a conclusion for a call for further research addressing neurodevelopmental effects on humans (EPA, 2025).

On November 2, 2023, the U.S. Court of Appeals for the Eighth Circuit vacated the EPA's final rule, revoking all food tolerances for CPF, and remanded the matter for further proceedings (EPA, 2025). Following the court's mandate on December 28, 2023, all previously existing CPF tolerances were reinstated (EPA, 2025). On February 5, 2024, the EPA issued a Federal Register notice amending the Code of Federal Regulations (CFR) to reflect this reinstatement (EPA, 2025). The court ruled that the EPA should have considered modifying tolerances instead of full revocation, referencing 11 specific crop uses identified in the EPA's 2020 Proposed Interim Registration Review Decision (PID) (EPA, 2025). In response, the EPA released a proposed tolerance rule in December 2024, with a public comment period open until February 10, 2025 (EPA, 2025). In the interim, the EPA issued a proposed rule to revoke all tolerances for CPF, except for 11 food and animal feed crops produced in specific states that were assessed in the 2020 proposed interim decision: alfalfa, apple, asparagus, cherry (tart), citrus, cotton, peach, soybean, strawberry, sugar beets, and wheat (spring and winter) (EPA, 2025). This revocation limiting states to select crops had the potential, based on available data gathered by the EPA, to decrease the average annual pounds of CPF applied in the U.S. by 70% compared to historical usage (EPA, 2025).

Pesticides are applied during cultivation and postharvest to prevent crop damage, to prolong storage life, and maintain quality. To minimize consumer risks, the U.S. implemented maximum residue levels (MRLs) overseen by the EPA to prevent overexposure (Huertas-Perez, 2019). MRLs are the highest level of pesticide residue that is legally tolerated in or on food or feed when pesticides are applied correctly using good agricultural practices (GAPs) (EPA, 2011). The EPA established MRLs for pesticides under the Federal Food, Drug, and Cosmetic Act, setting health-based exposure thresholds (EPA, 2000). Revised on September 17, 2024, the U.S. set a current tolerance level, or MRL, of 0.3 mg/kg or ppm for soybean seeds (EPA, 2011). The CFR shares the maximum tolerance levels depending on the commodity or food type, ranging from 0.05 to 15 ppm (EPA, 2011). In the European Union (EU), limits of detection (LOD) are the same as MRLs in the U.S., and the LOD since November 13, 2020, for CPF in the EU is 0.01 ppm for all food (EU Law, 2008). The remaining international harmonization trade reference for food safety and tolerances, including that for Canada and Mexico, then turns to the generally

accepted MRL from CODEX, allowing 0.1 ppm of CPF residue (EPA, 2020).

A 2020 health risk assessment determined the acceptable daily intake (ADI) of CPF as 0.001 ppm per d over a lifetime, meaning exposure per kg of body weight should not exceed 0.001 ppm (Wolejko et al., 2022). The acute reference dose (ARfD), the maximum allowable CPF exposure within 24 h, is set at 0.005 ppm per kilogram of body weight per d (Wolejko et al., 2022). The ARfD is higher than the ADI because the body can tolerate short-term exposures to elevated doses without immediate adverse effects (EFSA, 2019). The U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) enforce CPF residue limits in food products, ensuring compliance with the EPA standards (GAO, 2025). The FDA regulates 80% of the U.S. food supply, including fruits, vegetables, dairy, and processed non-meat foods, while the USDA regulates meat, poultry, some eggs, and Siluriformes fish products (GAO, 2025). The FDA Food Safety Modernization Act (FSMA), signed in 2011, mandates domestic and international food facility inspections to prevent contamination, including CPF residues that may pose chemical safety concerns (GAO, 2025).

C. Effects of Chemical Contamination in Humans

CPF exerts its toxic effects on both insects and humans by inhibiting AChE, an enzyme crucial for nervous system function (Sud & Kaur, 2011). AChE breaks down the neurotransmitter ACh to prevent overstimulation of nerve cells. When CPF inhibits AChE, ACh accumulates in synaptic junctions in between individual neurons, leading to excessive nerve signaling. This overstimulation can result in neurotoxicity, including symptoms such as nervousness, delirium, hallucinations, and psychoses (Rahman et al., 2021). Organophosphates (OPs), like CPF, can also act as alkylating agents, causing DNA damage (Wolejko et al., 2022).

CPF exposure, particularly during critical developmental windows, poses risks to human health, with the most vulnerable periods spanning from early pregnancy to adolescence (Ding et al., 2024). Research links prenatal CPF exposure to reduced birth weight, lower IQ, and delayed motor development in children (Rahman et al., 2021). Epidemiological studies show CPF exposure correlates with cognitive deficits, even at levels below current regulatory toxicity thresholds, with younger individuals being more vulnerable (Wolejko et al., 2022). Animal studies demonstrate that CPF exposure during gestation affects brain structure and function,

leading to delayed neurological development (Ambali & Ayo, 2011).

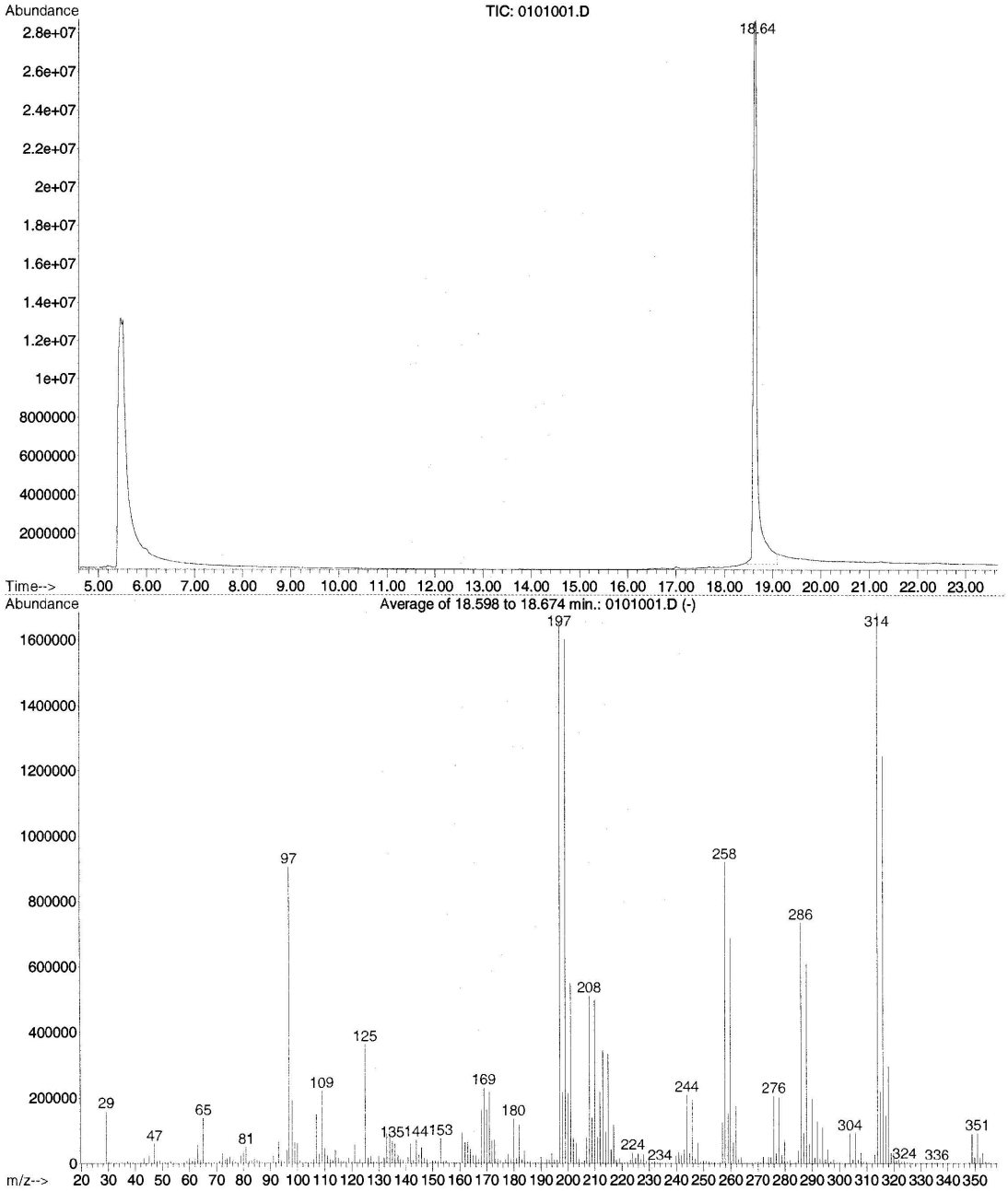
CPF exposure occurs through ingestion, inhalation, and dermal absorption. While oral and inhalation exposures are the primary routes, dermal exposure can still contribute to CPF toxicity (EPA, 2020). Alizadeh et al. (2018) found that after oral CPF ingestion, 70% of its metabolite, 3,5,6-trichloro-2-pyridinol (TCP), was excreted in urine, whereas only 3% was recovered following dermal exposure. The reduced dermal absorption is attributed to the protective keratinized skin layers (Rahman et al., 2021). However, exposure risks vary based on the exposed skin area and contact duration (Rahman et al., 2021). Understanding CPF exposure pathways and mitigation strategies is essential for reducing health risks. Ongoing regulatory scrutiny and scientific research continue to inform policies safeguarding human health and environmental integrity.

D. Chemical Detection Methods

Accurate and efficient detection of pesticide residues in food and crops is essential for safeguarding human health, ensuring food safety, minimizing environmental impact, supporting trade, and maintaining consumer confidence. Various chemical techniques have proven highly effective in identifying pesticide residues in agricultural commodities, including soybeans. This report focuses on peer-reviewed studies published primarily since 2000, specifically examining chemical detection methods used for CPF residue analysis in soybeans.

Gas chromatography (GC) provides sensitivity and resolution for separating and identifying distinct components within a multiple-component system, particularly for pesticides with low detection limits (Munir et al., 2024). GC is especially useful for detecting volatile pesticides that may evaporate unpredictably at ambient temperatures. Evolving technologies like mass spectrometry imaging (MSI), when coupled with GC (as GC-MS), enable selective detection and analysis of pesticide residues by examining ion fragmentation patterns and distributions (Maloof & Tucker, 2022). Since molecules must be in the vapor state for electron ionization, MSI pairs effectively with GC, which vaporizes liquids into gaseous form for

Figure 1. Total ion chromatogram and mass spectrum of chlorpyrifos (CPF) as detected by GC-MS. The upper panel shows the total ion chromatogram (TIC) with a prominent CPF peak at approximately 18.64 min, indicating its retention time. The lower panel displays the corresponding mass spectrum with characteristic ion fragments at m/z 97, 125, 197, 258, 286, and 314, confirming the compound's identity. The base peak at m/z 314 reflects the most abundant fragment, supporting the detection of CPF even at trace levels (FAO, 2015).



analysis. MSI offers high sensitivity, low detection limits, and the ability to determine both the identity and concentration of pesticide residues. It is particularly valuable for visualizing

pesticide residue drift and accumulation in food commodities, supporting multi-residue detection within a single analytical run. In GC-MS, the retention time corresponds to the moment a compound elutes from the column, while the mass spectrum identifies the unique pattern of ionized fragments. Figure 1 illustrates this with two panels: the upper panel displays the total ion chromatogram (TIC), showing a dominant CPF peak at approximately 18.64 min, confirming its elution and presence; the lower panel presents the mass spectrum for that peak, with characteristic ions at a mass-to-charge ratio (m/z) of 97, 125, 197, 258, 286, and 314, supporting the structural identity of CPF (FAO, 2015). The higher the peak height, the more a particular ion or chemical exists within the sample. The base peak at an m/z of 314 represents the most abundant ion fragment and confirms CPF's detection, even in trace amounts. These parameters, retention time from GC, and m/z fragmentation patterns from MS, collectively ensure both the accuracy and specificity of CPF identification in pesticide residue analysis (FAO, 2015). Table 1 further identifies the GC-MS peaks as they fragment from the chemical formula of $C_9H_{11}Cl_3NO_3PS$ in the experiment, contributing to the peaks in the mass spectrum (Zheng et al., 2016).

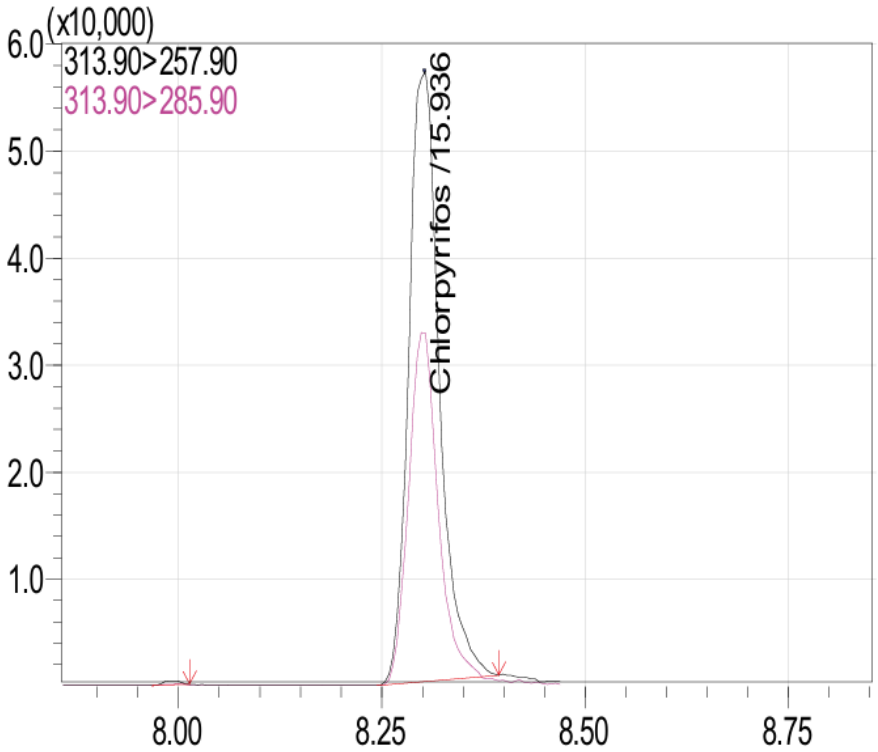
Table 1. Summary of the main m/z values observed in chlorpyrifos in Figure 1, including molecular ions and specific fragments such as the TCP metabolite (m/z of 197), aiding in compound identification, and residue confirmation (adapted from Sinha, 2011; Pengphol et al., 2012; and Dai et al., 2017).

m/z	Fragment	Fragment Description
314	[CPF]^+	Molecular ion of chlorpyrifos; confirms intact CPF presence (base peak).
286	[CPF – C_2H_5]^+ or [CPF – HCl]^+	Loss of ethyl group or hydrogen chloride from parent ion.
258	Further fragmentation	Additional loss from phosphorothioate group.
197	TCP ion ($C_5H_2Cl_3NO$)	3,5,6-Trichloro-2-pyridinol (TCP), a major degradation product and CPF metabolite.
125	Pyridyl/phosphate-related fragment	Likely derived from partial cleavage of the ring or phosphorus-containing structure.
97	$PO(C_2H_5)_2$^+ or similar	Phosphorus-oxygen-ethyl ion; typical of organophosphate pesticides.

High-performance liquid chromatography (HPLC) is a powerful analytical method widely used in pesticide residue analysis due to its high sensitivity and ability to separate multiple

components in a sample (Munir et al., 2024). This technique is especially suited for identifying and quantifying pesticides at trace levels, enabling the concurrent detection of numerous analytes in a single run. In conjunction with HPLC, ultraviolet spectroscopy (UVS) serves as a complementary method by measuring the absorbance of compounds at specific UV wavelengths. Unlike MSI, which provides structural information based on m/z, UVS detects compounds based on their optical absorption, which is particularly useful for compounds like CPF that exhibit strong UV absorbance (Anbarasan, 2022). Figure 2 illustrates the UVS absorbance peaks detected during HPLC analysis of a tomato sample, used to evaluate the effectiveness of a 3 min water washing treatment in reducing CPF residues (Elmastas et al., 2023). These peaks

Figure 2. HPLC-UVS chromatogram of chlorpyrifos residues in a tomato sample before and after washing. The black peak at 15.936 min represents chlorpyrifos in the unwashed sample (from an extended graph), while the shorter red peak at 8.25 min reflects the presence of chlorpyrifos-methyl, a degradation product, following a 3 min water wash. The x-axis shows retention time (min), and the y-axis indicates UV absorbance (mAU), with peak height corresponding to compound concentration (adapted from Elmastas et al., 2023).

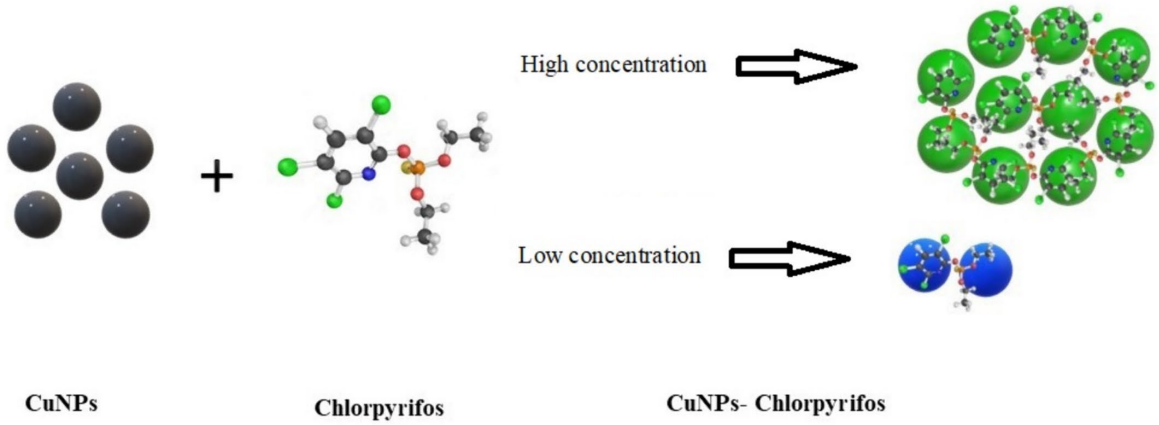


correspond to retention times where CPF and related compounds eluted and absorbed UV light, confirming their presence in the sample. The magnitude of each absorbance peak reflects the concentration of the detected compound, while the retention time helps identify it based on

known chromatographic behavior. This HPLC-UV spectroscopy pairing was essential for quantifying residue levels before and after treatment interventions such as washing, as demonstrated by the comparative peak heights. A reduction in peak height after washing indicates a decline in CPF concentration, validating the treatment's effectiveness although not significant enough to reach MRLs in this case (Elmastas et al., 2023). The retention time also shifted from 15.936 min to 8.25 min, consistent with the formation of CPF-methyl, a lower-concentration metabolite resulting from partial degradation during washing. UVS quantification of CPF is referenced in the review to illustrate the effectiveness of specific mitigation treatments, including O_3 and cold plasma, to reduce CPF on soybeans. While HPLC, GC, MSI, and UVS are traditional methods for detecting pesticide residues, one disadvantage is that these methods are costly, time-consuming, and depend on skilled personnel (Sheikh & Shekarchizadeh, 2024).

A newer method, colorimetric sensing, uses a colorimetric indicator based on copper nanoparticles (CuNPs) to detect heavy metals, other analytes, and pesticides including CPF (Sheikh & Shekarchizadeh, 2024). The indicator relies on copper's ability to bind with sulfur compounds and is a simple, cost-effective, accurate, and highly selective method for detecting CPF. In the presence of CPF, the indicator's color changes from blue to green, both indicating the presence of CPF, with green being a higher and blue indicating a lower concentration, as shown in Figure 3.

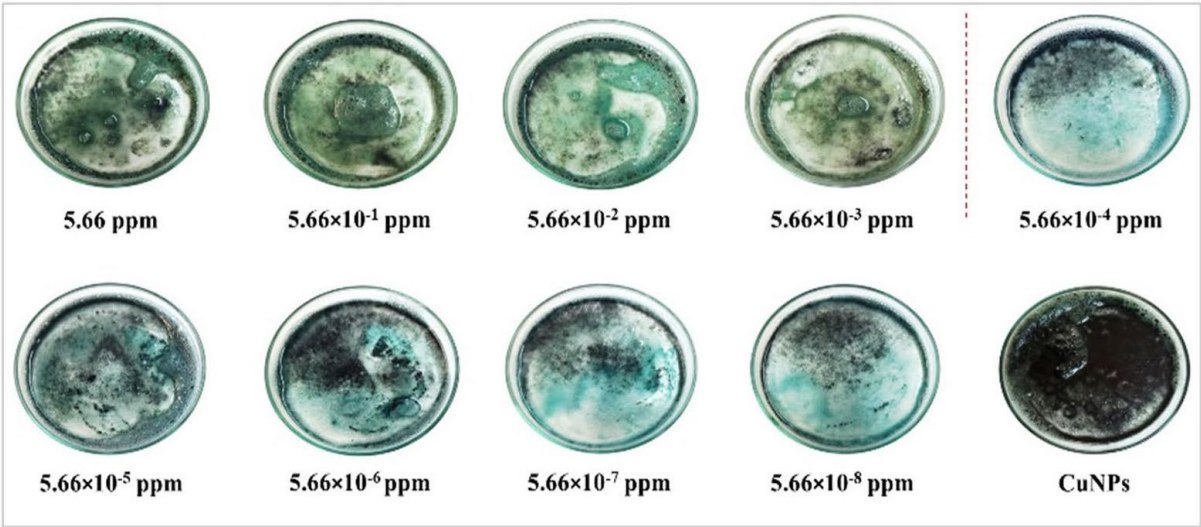
Figure 3. Showing the color shift to green or blue, depending on the chlorpyrifos concentration (from Sheikh & Shekarchizadeh, 2024).



A color shift to blue indicates that the product meets safety and health standards. The results of this colorimetry method can be easily observed visually, eliminating the need for additional devices and equipment. The unique optical properties of metal nanoparticles enhance their visual detection (Sheikh & Shekarchizadeh, 2024). These materials exhibit noticeable color changes

when aggregating or growing, resulting in visual detection. In Figure 4, the color indicator's appearance changes at different CPF concentrations. Initially, CuNPs are black (bottom right), showing no detectable CPF residue present. Upon adding CPF, the visible color shifted to green (high CPF concentration) or blue (low CPF).

Figure 4. Color change of Cu nanoparticle-based indicator in different concentrations of chlorpyrifos, highest to lowest (top left to bottom right). The dotted line shows when the concentration goes from high to low CPF (from Sheikh & Shekarchizadeh, 2024).



In a study by Wolejko et al. (2022) CPF concentrations in cucumber samples were investigated to check the efficiency of detecting various concentrations ranging from 5.66 x 10^{-8} to 5.66 ppm CPF. The dotted line in Figure 4 delineates when CPF concentrations went from low to high, with low showing adherence to the ADI of CPF at 0.001 ppm per d mg/kg (ppm) of body weight (Wolejko et al., 2022).

E. Residue Mitigation Methods

The focus of this review was to investigate what methods worked to remove or destroy the remaining CPF on soybeans to prevent potential chemical contamination at the point of human consumption. Various mitigation methods were examined to reduce CPF residues and minimize human dietary risk. These included naturally occurring environmental factors such as storage time and light exposure and processing techniques such as rinsing with water, ultrasound-assisted washing, O_3 water treatment, heat application, and cold plasma. The effectiveness of each method was assessed to identify the most viable solutions for food safety to

ensure proper mitigation if soybeans exceed the 0.3 ppm MRL of CPF after distribution (EPA, 2011).

1. Effects of Environmental Factors

a. Effect of Time in Storage

Several studies explored CPF residues remaining after time due to storage conditions. Soybeans and other commodities are commonly sprayed with pesticides during storage and shipment after harvest to prevent damage from pests (Miyahara & Saito, 1994). Results fluctuated slightly between studies, depending on the different storage conditions, such as ambient temperature, humidity, airflow, and light exposure. In statistical terms, the variations were not significant, meaning there is not enough evidence at the 95% confidence level ($p > 0.05$) to conclude that storage conditions caused a real difference in residue levels. One study explored the dissipation of CPF residue in soybeans by comparing how long the soybeans were in storage under local weather conditions in China for up to six months using GC-MS (Zhao et al., 2014). Residues were recorded at different time intervals by length of time in d of storage (0, 15, 31, 60, 90, and 112 d). The initial concentration at day 0 was 2.60 mg/kg (ppm), and the residue decreased by about 62% to 0.98 mg/kg after 112 d, as shown in Table 2. This information and mathematical calculations showed a half-life dissipation of about 99 d, meaning it took 99 d to decline from 2.6 ppm to 1.3 ppm. A result of 0.98 ppm after 112 d in storage still indicated a dietary risk coming in over three times the CPF tolerance of 0.3 ppm (EPA, 2011).

Table 2. Residue levels of CPF in stored soybeans at various times (in days) during storage (adapted from Zhao et al., 2014).

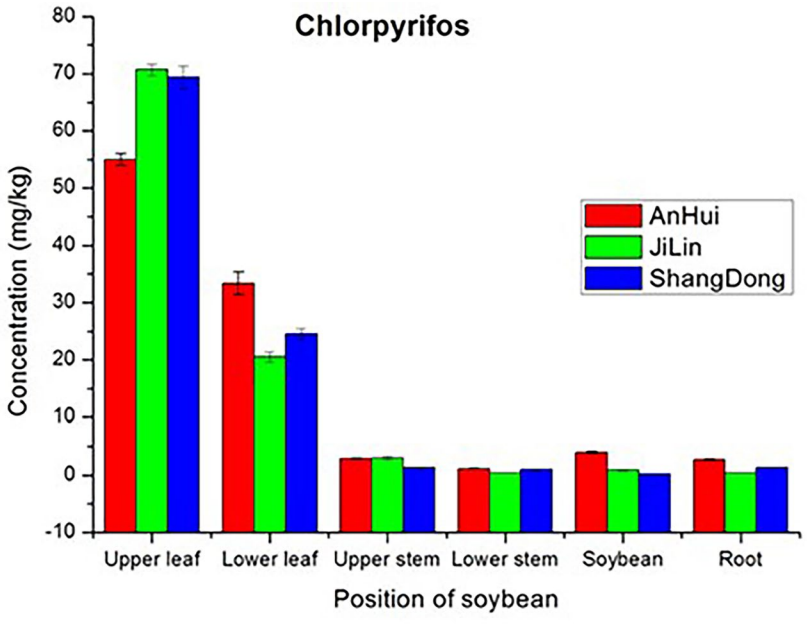
Time (days)	Chlorpyrifos Concentration (mg/kg)	Degradation rate (%)
0	2.60	0.0
15	2.49	4.2
31	1.90	26.9
60	1.66	36.2
90	1.61	38.1
112	0.98	62.3

Another study conducted in Egypt referenced in the study by Zhao et al. (2014) reported a 91% reduction in CPF residues after 24 weeks of storage (El-Maghraby, 2000). This storage

duration was approximately two months longer than Zhao's four-month study in China Both studies referred to storage under ambient conditions, which refers to the actual temperature of the surrounding air, although exact temperatures were not reported. This introduced some uncertainty in direct comparison between the studies, as environmental temperature fluctuations could influence CPF's degradation rate. The 9% remaining of an application dose of 45 ppm still left 4.05 ppm of CPF residue, which remained above the MRL.

Another study in China showed insight across three major production provinces on the precise location of CPF concentrates when sprayed pre-harvest on an actively growing soybean plant (Figure 5; Tong et al., 2021). The positions of the studied plants are the upper leaf, lower leaf, upper stem, lower stem, soybean, and root (Tong et al., 2021). Although this study aimed to ensure the efficacy of CPF insecticidal application rates, it is insightful to see that more residues existed on the soybean leaves, which are not consumed. The residue levels of CPF on the beans of the soy plant that are consumed were detected at 0.23-3.95 ppm with a degradation half-life of 3.28-5.36 d (Tong et al., 2021). This indicated that when applying CPF pre-harvest, residues decreased on a growing plant to 0.115-1.975 ppm after less than a week. In terms of storage, after nine months, CPF residues remained stable, and very little dissipation occurred thereafter.

Figure 5. The distribution of chlorpyrifos in the soybean plant system by growing regional provinces in China (from Tong et al., 2021). The error bars (lines extending above and below each bar) represent the standard deviation ($p < 0.05$) from replicate samples, reflecting the variability of CPF concentrations within that plant tissue.



b. Effect of Direct Sunlight Exposure and UV-radiation Exposure

Natural sunlight and specific wavelengths of non-visible light were investigated to evaluate the effectiveness of mitigating CPF residues in soybeans (Massoud et al., 2014). In the pre-harvest phase, whole soybean plants were treated in field plots and monitored for CPF residues across leaves, pods, and seeds. Samples collected at regular intervals up to harvest demonstrated a time-dependent decline in residues, supporting the use of a 15-d pre-harvest dwell time to reduce residues to below CODEX limits (0.1 ppm) adhered to by Egypt as opposed to the MRL set by EPA (0.3 ppm) for the U.S. (Massoud et al., 2014). Samples were collected from treated and untreated plots at intervals 1, 3, 5, 10, and 15-d post-application as shown in Table 3 (Massoud et al., 2014). Data showed that CPF residues on and in leaves, pods, and seeds decreased with time, with a residue below 0.1 ppm for all three sample sites after a 15-day dwell time under natural field conditions before harvest.

Table 3. Chlorpyrifos residues and loss rates on and in soybean leaves, pods, and seeds with means followed by a different lowercase letter are significantly different at a 95% confidence level ($p < 0.05$) (adapted from Massoud et al., 2014).

Time of application (days)	Residues in leaves		Residues in pods		Residues in seeds	
	Mean µg /gm	% Loss	Mean µg /gm	% Loss	Mean µg /gm	% Loss
Initial	27.53±0.25 a	00.00	12.41 ±0.53a	0.00	N.D.	0.00
1	12.94±0.23 b	52.98	3.25± 0.1b	73.79	0.22 ±0.01a	0.00
3	11.73± 0.10c	57.41	1.68±0.01 c	86.44	0.44 ±0.03b	0.00
5	10.78± 0.21d	60.82	0.53±0.04 d	95.7	0.83± 0.06c	0.00
10	4.87± 0.4e	82.31	N.D.	100	0.63±0.04 d	25
15	1.83±0.01 f	93.34	N.D.	100	0.10±0.01 f	88
49 (Harvest day)	N.D.	≈100	N.D.	100	N.D.	100
K`	0.312	--	0.87	--	0.083	--
RL_{50} (days)	2.22	--	0.79	--	8.34	--

N.D.: not detected. Limit of detection for chlorpyrifos 0.01 ppm
Means followed by a common letter are not significantly different

In contrast to the pre-harvest field trial conducted on whole soybean plants, a separate set of experiments in the same study was designed to isolate the impact of specific environmental conditions on the photodegradation of CPF (Massoud et al., 2014). In this experiment, CPF was

applied in solution form onto the surface of sterile Petri dishes, allowed to dry, and then exposed to direct outdoor sunlight consisting naturally of UVA (315-400 nm) and UVB (280-315 nm) light for 0, 1, 3, 6, 12, 24, 48, and 96 h (WHO, 2016 and Massoud et al., 2014). A second group was exposed to short UVC (100-280 nm defined by WHO) rays at a specific 254 nm, considered a higher energy wavelength, at a distance of 12 cm at the same time points. This controlled approach allowed researchers to monitor degradation independently of plant metabolism, surface interactions, and environmental variability—factors such as plant surface characteristics, wax layers, and leaf architecture, which can shield residues from full light exposure in field-grown crops (Massoud et al., 2014). Results showed a rapid dissipation of CPF in this controlled system. After just one h, CPF levels were reduced by 66.15% under sunlight and 69.49% under UVC exposure. Complete degradation (100%) was observed after 6 h of sunlight exposure and after 24 h of UVC exposure. These findings demonstrate that CPF is highly susceptible to photodegradation under direct light, particularly when not bound to complex plant surfaces or protected by canopy shading (Massoud et al., 2014). Continuous degradation correlated with the exposure period; the extended exposure period gave a higher loss rate for CPF. Photodegradation by sunlight is one of the most promising methods for pesticide degradation (Massoud et al., 2014). CPF degradation by sunlight was faster than UVC radiation, and this may be because CPF UV absorbance is over 290 nm (WHO, 2016). Like many organic compounds, pesticides have distinct absorption characteristics when exposed to UV light (Katagi, 2004). The degree to which a pesticide absorbs UV light is related to its chemical structure, particularly the functional groups that can absorb energy in the UV range between 200 to 400 nm (Katagi, 2004). Loss rate values for CPF residues were 99.72 and 100% at 3 and 6 h after exposure, respectively, as shown in Table 4 (Massoud et al., 2014). However, these findings reflected the behavior of CPF in an artificial exposure scenario and do not directly replicate field conditions. Therefore, while photodegradation by sunlight may be promising, these results should be interpreted cautiously, as they were not derived from whole-plant field exposure.

Table 4. Influence of direct sunlight and UV radiation on the dissipation rate of chlorpyrifos residues (adapted from Massoud et al., 2014). Means followed by a common letter shown by column are not significantly different at the means ± standard deviation of the triplicate samples.

Time (hr)	Sunlight		UV radiation	
	Mean µg found	% Loss	Mean µg found	% Loss
Initial	500.00[a]	0.00	500.00[a]	0.00
1	169±2.4[b]	66.15	152.55±0.54[b]	64.49
3	1.36±0.10[c]	99.72	94.85±0.9[c]	81.03
6	0.00[d]	100.00	85.67±0.7[d]	82.86
12	0.00[d]	100.00	40.22±1.1[e]	92.00
24	0.00[d]	100.00	0.16±0.01[f]	100.00
48	0.00[d]	100.00	0.00[g]	100.00
96	0.00[d]	100.00	0.00[g]	100.00
144	0.00[d]	100.00	0.00[g]	100.00
K'	1.51	--	0.31	--
$T^1/_2$ (hr)	0.46	--	0.79	--

Values are means ± standard deviation (n=3)
Limit of detection for chlorpyrifos 0.01 ppm
Means followed by a common letter are not significantly different at the 5% level

2. Effects of Processing

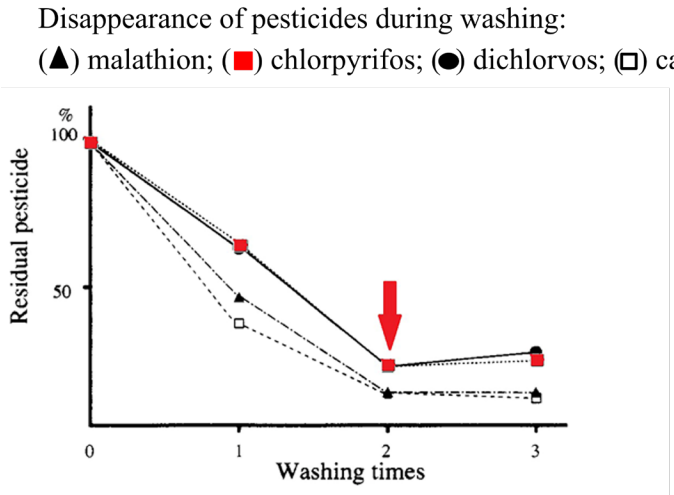
This section reviews both conventional and more advanced techniques for reducing or removing pesticide residues from soybeans intended for consumption. Several non-thermal treatments, as well as wet and dry thermal treatments, were explored.

a. Effects of Rinsing with Water

Rinsing plant-based foods with water before consumption is well-known residentially and is one of the simplest and most common options used commercially as an initial mitigation factor in reducing chemical and biological contaminants (Kaushik et al., 2009). The elimination of pesticide residues from the surface of soybeans (the seeds) depends on the starting pesticide concentration and the octanol-water partition coefficient (K_{ow}) which refers to the lipophilic (fat solubility) and hydrophilic (water solubility) properties (Zhao et al., 2014). Zhao et al. (2014) explained that compounds with a K_{ow} value greater than 4 generally have a high potential for

bioaccumulation in the fatty tissues of living organisms with a low affinity for water. Conversely, substances with a low K_{ow} are easier to remove by washing with water. The K_{ow} coefficient for CPF is 4.7001 at 20°C meaning it has a higher potential to accumulate in fatty tissues of living organisms (FAO, 2015). It was found that during rinsing in tap water, physical agitation, such as rubbing, increased the elimination of pesticides from the seed (Munir et al., 2024). A review study showed that CPF at an initial level of 11.2 ppm applied to soybeans dissipated by 80 to 90% after washing with tap water twice (Kaushik et al., 2009). Research on washing cited by Kaushik et al. (2009) referenced an older yet relevant study showing that washing soybeans caused the concentration of CPF in or on the soybeans to decrease by 20% with the first wash and up to 90% with the second (Miyahara & Saito, 1994). In this study, soybeans were first soaked in water for 12 h before the washing process was carried out without clarifying the purpose, which is a step that likely enhanced the effectiveness of surface pesticide removal. However, there was no further reduction with subsequent washings, as shown in Figure 6, illustrating the lowest CPF residue after two washes (Miyahara & Saito, 1994). The concentrations of pesticides were monitored by GC. The results suggested that sprayed pesticides remain as microparticles on the soybeans' surface (Kaushik et al., 2009). These are easily removed by mechanical stirring in water and soaking may also aid in loosening surface-bound residues prior to mechanical agitation (Kaushik et al., 2009). The remaining residues not removed by washing may exist in the soybeans as they still show on the sensitive GC-MS results (Kaushik et al., 2009).

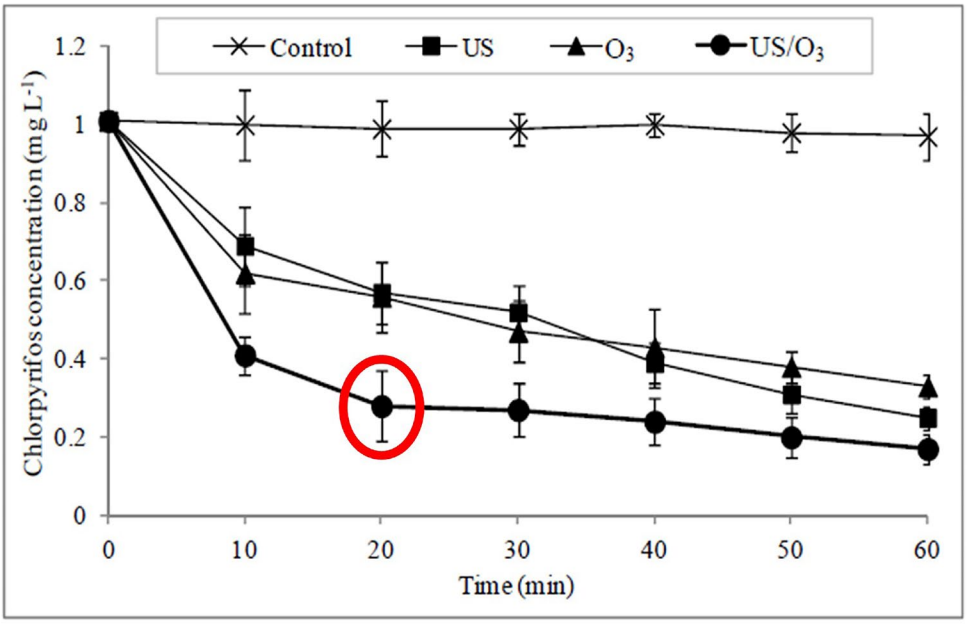
Figure 6. Decreased pesticide residues showing chlorpyrifos (in red) during washing. The arrow highlights the lowest residue after two washes (adapted from Miyahara & Saito, 1994).



b. Effects of Ultrasound

Ultrasound (ULS) is derived from ultrasonic sound waves in a frequency of sound above what humans hear (Munir et al., 2024). The ULS cleaning process creates cavitation bubbles produced by high-frequency pressure to agitate the water medium. Munir et al. (2024) explained that the process forms tiny bubbles and causes the water molecules to implode due to pressure changes in the water. The high-energy impact from the pressure changes and cavitation of the bubbles produces enough force to dislodge residues adhering to the surface of an object (Fu et al., 2020). ULS cleaning produces a very effective cleaning procedure that requires little to no additional chemicals. One study indicated that ULS and O_3 applied in combination had a synergistic effect in reducing CPF concentration with most of the degradation occurring within the first 10 min (Figure 7; Pengphol et. al, 2012). Each data point on the graph represents the mean CPF concentration at that time point, while the vertical bars attached to each point are error bars that show a standard error from replicate measurements. It may be necessary to continue both techniques for 20 min to reach 0.3 ppm MRL.

Figure 7. Chlorpyrifos concentrations in ppm (mgL-1) after treatment with ultrasound, ozone, and a combination of the two, highlighting the fastest reduction in red ($p < 0.05$) (adapted from Pengphol et al., 2012). The values are expressed as mean ± standard error (S.E.) of measurements made on three replicates of treatment.



c. Effect of Ozone Gas

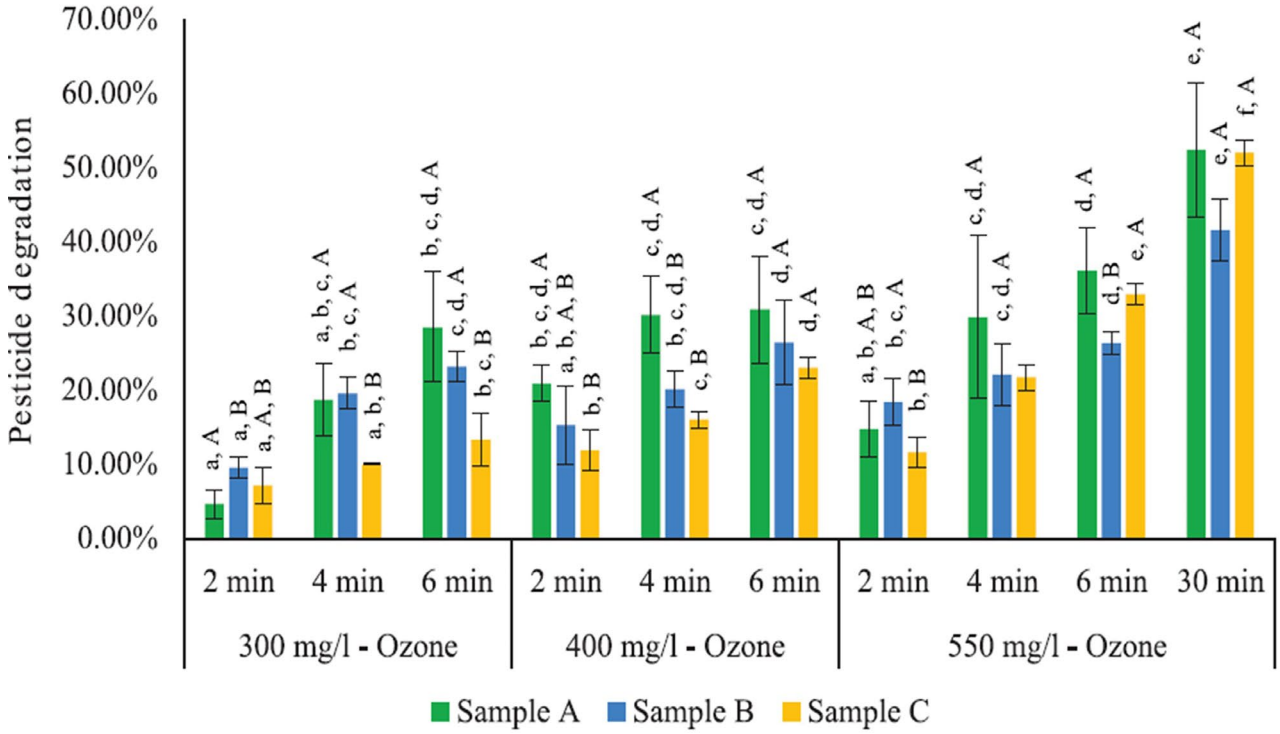
O_3 is a colorless oxidizing gas (an electron donor in chemistry) ready to react chemically with various substances, adding an oxygen atom to the receiving chemical molecular structure (Peters et al., 2004). Peters et al. (2004) explained that an oxidizer breaks down and destroys non-living chemical compounds including CPF, reducing potential health risks associated with pesticide consumption. Like hydrogen peroxide used residentially to clean wounds or kill microbes, O_3 is used industrially as a disinfectant (Pfuntner, 2022). From a food safety standpoint, a sanitizer, disinfectant, or sterilizer aims to reduce biological microorganisms of public health importance (Pfuntner, 2022). Table 5 shows that O_3 is a stronger oxidizing agent and more reactive than hydrogen peroxide or chlorine, which are more familiar to consumers (Peters et al., 2004).

Table 5. Relative oxidation power of common oxidants (adapted from Peters et al., 2004).

Oxidant	Relative Oxidizing Power (Cl_2 = 1.0)
Fluorine	2.23
Hydroxyl radical	2.06
Atomic oxygen (singlet)	1.78
Ozone	**1.50**
Hydrogen peroxide	1.31
Perhydroxyl radical	1.25
Potassium permanganate	1.24
Chlorine dioxide	1.15
Bromine	0.80
Iodine	0.54

In the presence of CPF, O_3 reacts with the pesticide molecules, breaking them down into smaller ketones and reactive R species, which are far less toxic (Anbarasan et al., 2022). Although O_3 is very effective in mitigating CPF residues, it is valuable to understand what concentration is necessary without overusing one chemical to manage another. One report specific to soybeans evaluated three different O_3 concentrations (550 mg/L, 400 mg/L, and 300 mg/L) for their efficacy in oxidizing varying concentrations of CPF (sample A contained 1 mg, sample B contained 2 mg, and sample C contained 3 mg) relative to the exposure time (2, 4, or 6 min) (Anbarasan et al., 2022). The results in Figure 8 demonstrated that even with a higher O_3 concentration, a longer exposure time was less effective, with lower pesticide degradation

Figure 8. Chlorpyrifos percentage degradation by ozone in three different concentrations (from Anbarasan et al., 2022). Different lowercase alphabets between each treatment of the same sample indicate a 95% confidence level ($p < 0.05$) between the treatments, while different uppercase alphabets in different samples of the same indicate a 95% confidence level ($p < 0.05$) between the samples at the same treatment condition.



observed in the high-CPF infused samples with the 2 ppm sample degradation at 26.27% and the 3 ppm sample degradation at 32.80% (Anbarasan et al., 2022). This was due to a shielding effect, where oxidized pesticide aggregates formed on the seed surface, creating a barrier that limited O_3's ability to break down the pesticide. As a result, less O_3 reached the CPF in the high pesticide samples compared to the low pesticide samples. To overcome the shielding effect, soybean seeds were exposed to a higher concentration of O_3 (550 mg/l), which resulted in 52.12%, 41.5%, and 51.93% degradation in the samples containing 1 ppm, 2 ppm, and 3 ppm CPF, respectively (Anbarasan et al., 2022). In order to understand how long it took to achieve more degradation, Anbarasan et al. (2022) applied O_3 at the higher concentration for 30 min. At the greatest percent degradation of 51.93% in the sample starting at 3 ppm of CPF for 30 min, there would still be 1.67 ppm CPF remaining requiring additional mitigation factors. As previously discussed with ultrasound washing, O_3 can be applied simultaneously with additional wash methods that increase efficacy (Pengphol et al., 2012).

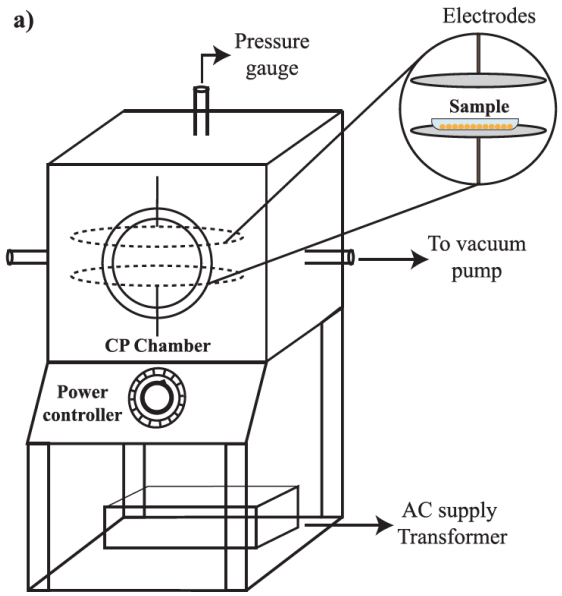
Regarding degradation efficiency, at 300 mg/L O_3, CPF degradation increased from 4.15% (2 min) to 28.2% (6 min). Higher concentrations of O_3 (400 mg/L and 550 mg/L) further improved degradation to 35.68% after 6 min. Higher initial CPF levels reduced degradation efficiency due to the formation of an oxidized CPF layer that restricted O_3 penetration. Even at 550 mg/L O_3 for 6 min, degradation was only 26.27% (2 ppm sample) and 32.80% (3 ppm sample). Increasing O_3 treatment to 30 min improved degradation to 52.12%–51.93% across different contamination levels, showing that longer exposure enhances effectiveness but is time-intensive.

d. Effect of Cold Plasma

Cold plasma (CP) is an emerging nonthermal technology for food used to eliminate harmful chemicals and microorganisms (Harikrishna et al., 2023). Plasma is considered the fourth state of matter where a gas is subjected to a high energy condition above the solid, liquid, or gas states (Harikrishna et al., 2023). Electrons are partially stripped away from the atoms, resulting in charged ions and free electrons ready to interact with and change the surfaces of materials or living cells. Harikrishna et al. (2023) elaborated on the novelty of CP, which works within a much lower temperature range (30-50^{o}C) than thermal plasma and does not rely on heat. Higher temperatures can damage food quality, flavor, and nutritional content. Depending on the specific application, CP can be generated in various ways. A study investigated the degradation of CPF using a low-pressure dielectric barrier discharge (DBD) air plasma system, operating at approximately 2 mbar under vacuum conditions (Anbarasan et al., 2022). Figure 9 illustrates how CP is generated by applying alternating current (AC) between polished aluminum electrodes, with the experiment varying in voltage levels (1.0 kV=25 W, 1.5 kV=50 W, and 2.0 kV=100W) and exposure times (2, 4, and 6 min) (Anbarasan et al., 2022).

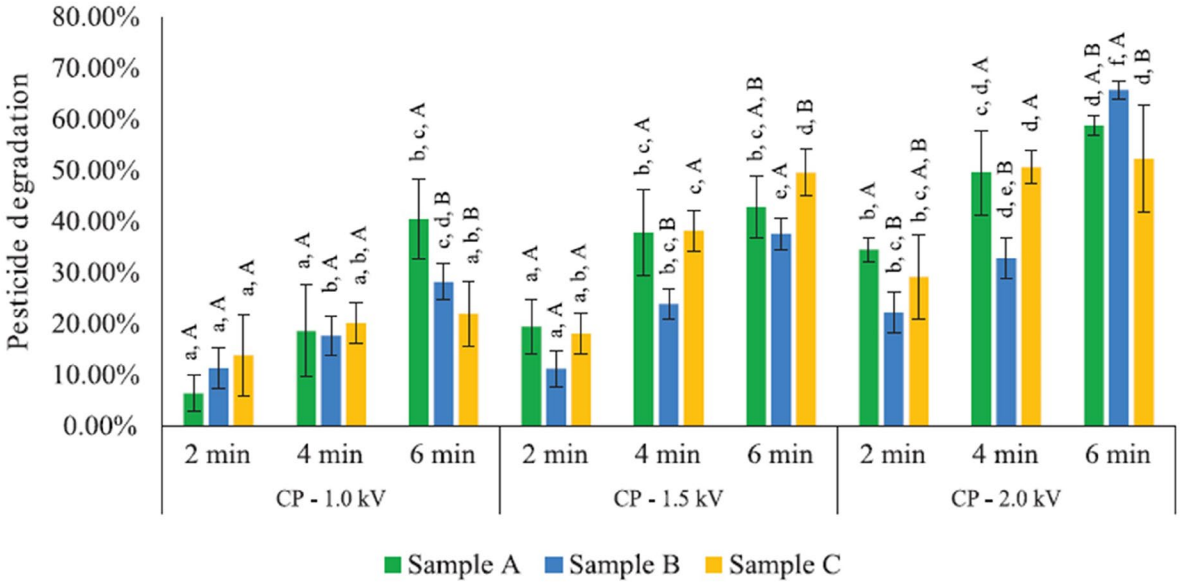
The DBD system employs a dielectric material, does not conduct electricity but can support an electric field like an insulator, wrapped around two flat metal electrodes to block electric currents, preventing sparks (Anbarasan et al., 2022). In the closed target chamber, a combination

Figure 9. Experimental setup of the cold plasma unit (from Anbarasan et al., 2022).



of inert or neutral gases flows between the two electrodes, where they are ionized to produce CP (Harikrishna et al., 2023). One electrode is connected to a high-voltage circuit, while the other is grounded. This type of discharge is non-equilibrium, either alternating or direct current, and can operate effectively across a range of gas pressures (Harikrishna et al., 2023). Anbarasan et al. (2022) also analyzed the effect of CP on CPF degradation at various voltages, exposure times, and pesticide concentrations. The use of CP showed higher CPF degradation with higher voltage levels and longer exposure times (Anbarasan et al., 2022). CP treatments increased the degradation of CPF from 6.6% to 40.65% after extending the treatment time from 2 to 6 min at 1.0 kV. When the voltage was increased to 1.5 kV and 2.0 kV, the degradation increased to 43.04% and 58.95% respectively, in the 1 ppm sample at 6 min as seen in Figure 10 (Anbarasan et al., 2022). At all pesticide concentration levels of 1 ppm, 2 ppm, and 3 ppm (sample C), the longest CP treatment of 6 min showed more CPF reduction than O_3 treatment at the same

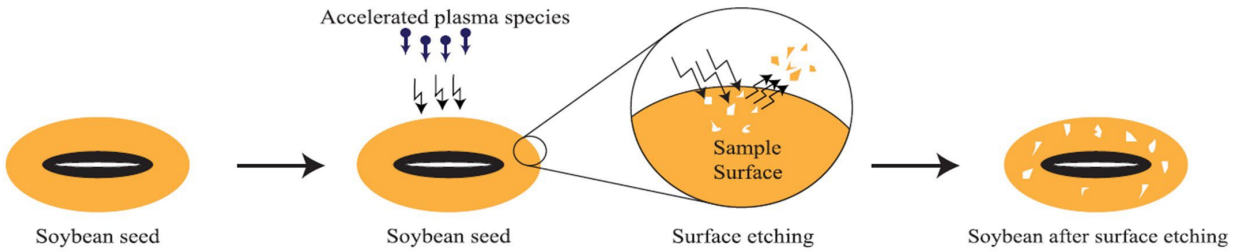
Figure 10. Chlorpyrifos percentage degradation by cold plasma in three different voltage levels (from Anbarasan et al., 2022). Different lowercase alphabets between each treatment of the same sample indicate the significant difference between the treatments, while different uppercase alphabets in different samples of the same treatment indicate the significant difference between the samples at the same treatment condition at a 95% confidence level ($p < 0.05$).



duration of time (Anbarasan et al., 2022). It takes five times longer (30 min) to achieve the same level of pesticide degradation with O_3 compared to that of CP.

When CP treatment is too intense (high voltage or prolonged exposure), it can cause over-etching, leading to at least 92% seed damage at low exposure times (1.0 kV, 2 min) and over 99% at longer exposures (6 min) (Anbarasan et al., 2022). Anbarasan et al. (2022) explained that etching in cold plasma (CP) occurs when accelerated gas ions bombard the surface, removing layers, and during oxidation (Figure 11). In CPF degradation, etching

Figure 11. Surface etching after cold plasma treatment to remove chlorpyrifos (from Anbarasan et al., 2022).



helps eliminate oxidized residues that could shield underlying contaminants. However, a seed is considered defective if it has visible cracks, blisters, or lacks its coat entirely (Zhu et al., 2020). In agriculture and food, a seed coat deficiency (SCD) score measures the extent of seed coat damage out of 100 seeds tested after exposure to different treatments. Zhu et al. (2020) further explained that a high SCD indicated significant damage to the seed coat, defeating the purpose. The etching of the seed coat is measured using contact angles, which measure the wettability of a surface by a liquid (Zhu et al., 2020). A higher contact angle number is ideal, indicating that water is not absorbed easily, and the seed coat is intact, protecting the seed (Figure 12; Anbarasan et al., 2022). Figure 13 shows the effect of CP on seed coat integrity, demonstrating that O_3 had minimal impact, and CP caused severe seed coat damage, raising SCD scores drastically.

Figure 12. Contact angle made by a water droplet on seed surface after ozone and cold plasma treatment showing lower angle with more damage to seed coat (from Anbarasan et al., 2022).

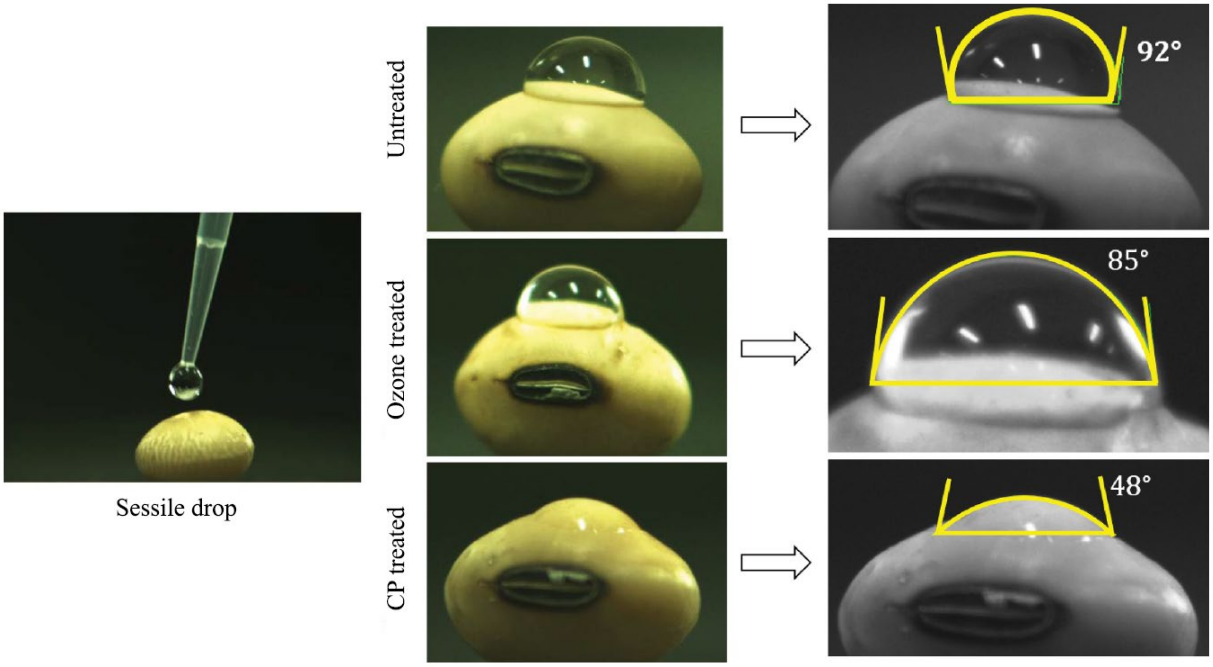
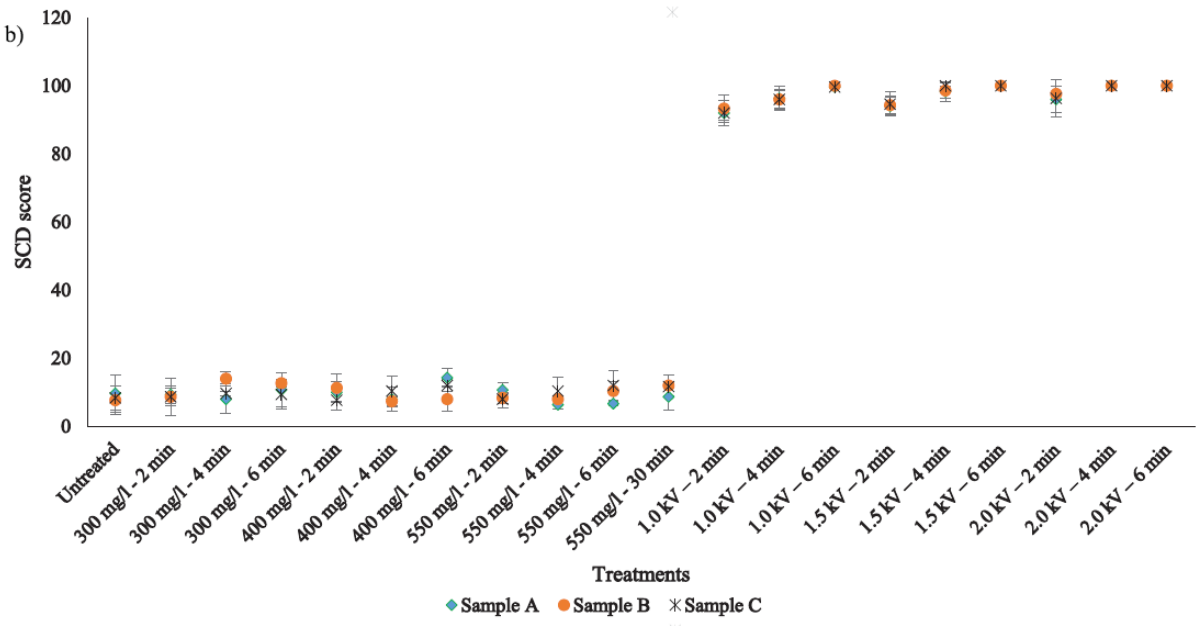


Figure 13. Effect of ozone (mg/l) and cold plasma treatment (kV) on the changes in seed coat deficiency score (from Anbarasan et al., 2022). The error bars represent the standard deviation of the mean values obtained from triplicate measurements (n=3).

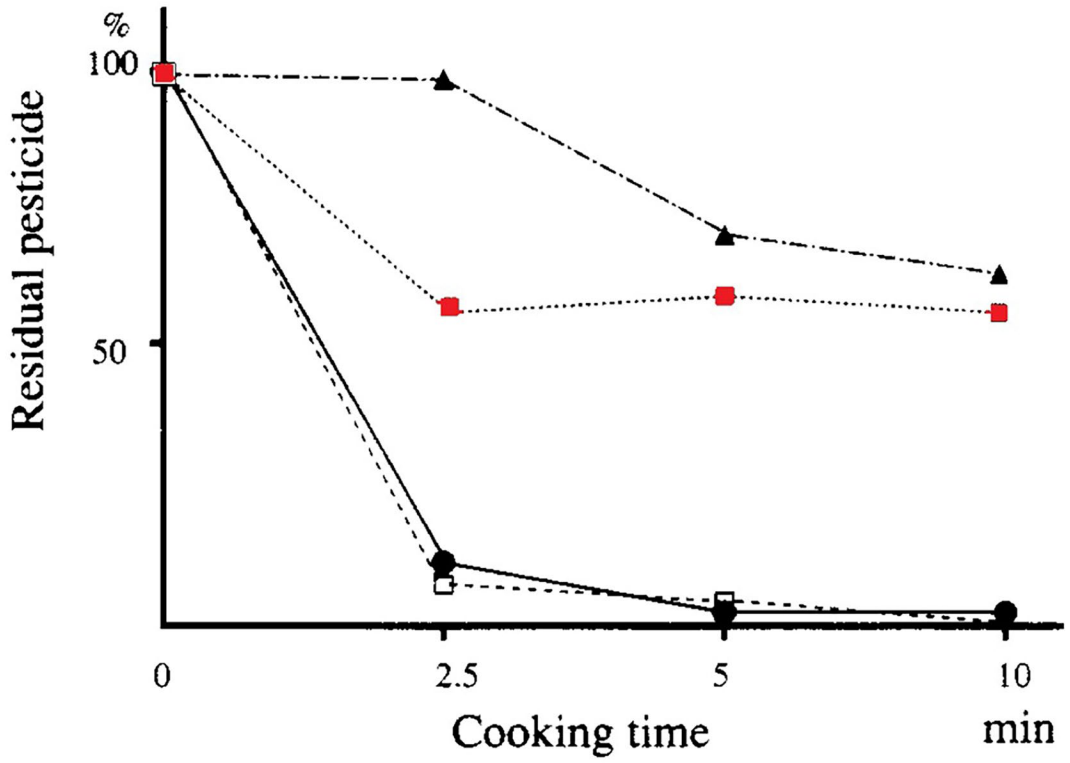


e. Effect of Thermal Treatments.

Heat treatment has been investigated as a postharvest strategy for mitigating CPF residues in soybeans, using a variety of processing approaches including dry heat, microwave irradiation, and wet cooking. One early study evaluated CPF degradation during each step of tofu processing, including washing, grinding, and heating (Miyahara & Saito, 1994). In this study, soybeans were first washed with water and ground into a homogenate before being subjected to heat. This work is one of the few that investigated CPF residue behavior in whole-bean cooking scenarios. The researchers found that cooking the ground soybeans at 100°C resulted in approximately 40% reduction in CPF after 2.5 min, but little additional degradation was observed after 5 and 10 min (Figure 14; Miyahara & Saito, 1994). Miyahara & Saito (1994) showed that despite the initial reduction, about 60% of CPF residues remained and concluded that CPF was relatively stable under these mild thermal conditions. The cooking process was only effective in reducing volatile or thermally unstable pesticides within the soybean homogenate (Miyahara & Saito, 1994).

Figure 14. Pesticide residue degradation percentage during cooking at 100ºC with the chlorpyrifos treatment (in red) (adapted from Miyahara & Saito, 1994).

(▲) malathion; (■) chlorpyrifos; (●) dichlorvos; (□) captan.



A separate experiment evaluated CPF dissipation during long-term storage and after heat processing (Zhao et al., 2014). Soybeans were treated with a CPF solution and stored in Petri dishes at ambient laboratory temperature for four months, with airflow allowed. Residue levels were monitored on d 0, 15, 31, 60, 90, and 112. Thermal treatment immediately after pesticide application, specifically microwave roasting at full power (800 watts) for 30 min, resulted in a 92% reduction of CPF on d 0 compared to raw soybeans (Table 6; Zhao et al., 2014). This finding supports previous work by Miyahara and Saito (1994), which showed a 50% reduction in CPF after 80 min of dry oven heating at 200°C. These extended cooking durations were applied to soybeans designated for oil extraction, a process relevant given that soybeans account for over 75% of vegetable oil used in human foods (Massoud et al., 2014).

Table 6. Chlorpyrifos residue levels after thermal processing (adapted from Zhao et al., 2014).

Matrix	Hot Press
Chlorpyrifos concentration (mg/kg)	Day 0
Raw soybeans	2.78
Roasted soybeans	0.21

Massoud et al. (2014) also evaluated CPF dissipation during heat processing of soybeans intended for soymilk production. Dry heating the whole bean reduced CPF residues by 33.58%, although this treatment also reduced soybean quality (Massoud et al., 2014). A reduction ($P<0.05$) of 70.3% was achieved after the beans were ground, mixed with water, and cooked at 90–95°C for 20 min, simulating standard soymilk preparation (Table 7; Massoud et al., 2014). These results demonstrated that combining grinding with wet thermal processing improved CPF degradation compared to dry heating alone.

Table 7. Influence of heat processes on removal of chlorpyrifos in soybean seeds (adapted from Massoud et al., 2014).

Commercial Processes	Mean Residue (ppm)	% Removal of Chlorpyrifos
Before treatment	14.06 ± 1.94^{a}	0.00
Dry heating	4.68 ± 0.72^{b}	33.28
Cooking in water	0.00^{c}	70.30

VI. Review Methodology

Originally, the overall subject of pesticide residues remaining on consumable food continued to surface in my work with North Dakota State University Extension. There was a need to understand more about potential chemical contaminations in commodities and how, if possible, to mitigate residues. Honing in on a topic, it was most important to find a particular pesticide that was surrounded by differing opinions and regulatory controversy. It was discussions with multiple agriculture and natural resources Extension agents who fielded inquiries that aided the final choice to review CPF. The majority of peer-reviewed studies used in this review were identified through a search of the Web of Science database online through Kansas State Libraries, using the key terms "chlorpyrifos," "residues," and "soybean." To enhance results, I also searched "soy"; other terms did not show results relevant to the topic of interest, such as "soy foods" or "limits." Familiarizing myself with the "Get It" button allowed

me to access article abstracts, leading to the purchase of EndNote version 21 for organizing articles.

Additionally, other online databases were used to ensure all available research on the topic was included, including Google Scholar and the NDSU online library. These databases added only two additional articles that were unavailable in the Kansas State University database. Evaluating source reliability involved reviewing titles, abstracts, and conclusions to ensure they contained pertinent information on CPF residue measurements. I requested three articles from the KSU interlibrary loan, two of which were in Chinese and translated by Google Translate, which proved helpful for the review. As my understanding evolved, I recognized the need to broaden my search to include governmental regulations and documents, such as those from the EPA, EU, and USDA, to explain tolerance limits effectively. This process revealed broader topics, including environmental safety and animal feed residues, providing a more comprehensive perspective on the implications of CPF usage.

VII. Discussion

The findings in this report highlight the significant influence that both naturally occurring environmental factors and processing techniques have on CPF residue levels in soybeans. Natural sunlight and time in storage were the two naturally occurring factors explored for their ability to degrade CPF residues. One study explored UVC rays along with natural sunlight albeit most UVC rays are blocked by the ozone layer in the atmosphere (WHO, 2016). Processing factors, including washing, ULS, O_3, CP, and heat, were examined with a focus on soybeans for human consumption. A few studies considered soybean oil and soymilk when research on whole soybeans was limited.

As for environmental factors, natural sunlight accelerated the degradation of CPF residues in soybeans. A complete 100% residue loss after 6 h of exposure to natural sunlight occurred due to absorption characteristics of CPF within the UVB range. CPF residues gradually dissipate by simply existing in storage over time. One study showed a 62% reduction over 112 d, though the remaining 0.98 ppm residual levels still exceeded the 0.3 ppm MRL on soybeans. Another study showed 91% dissipation of CPF residues after storage time; however, the 9% remaining of an application dose of 45 ppm still left 4.05 ppm of CPF residue, again far

exceeding limits. Storage alone is insufficient for complete CPF removal and varies depending on the ambient humidity, temperature, and oxygen levels. If beans are not exposed to natural sunlight, additional processing methods to enhance degradation are necessary.

Removal techniques, including washing with water, ULS, CP, and O_3 treatments, were also explored. Traditional tap water washing removed 80–90% of CPF while stirring after the second wash with fresh water each time, but it had limitations in further reduction. CP treatment reduced CPF residues by up to 58.95% within 6 min when applied at the maximum tested voltage in the experiment of 2.0 kV, starting from an initial concentration of 1 ppm. However, the remaining CPF residue was 0.41 ppm which is still above the 0.3 ppm CPF tolerance. Further, excessive CP exposure led to severe seed coat damage, with SCD scores exceeding 99%, making it unsuitable for human food applications requiring intact seeds. O_3 treatment, while slower than CP, avoided surface etching and effectively degraded CPF, with 52.12% reduction at 550 mg/L over 30 min, though efficiency was limited by shielding effects from oxidized pesticide residues. ULS combined with O_3 demonstrated enhanced CPF removal in 20 min, reaching residue levels below 0.3 ppm, making it a strong option with minimal adverse effects.

Thermal processing, including roasting, grinding, and cooking in water, reduced soybean CPF residues. Roasting soybeans for oil production can reduce CPF by 92%, reaching a residue level of 0.21 ppm, below the FDA's 0.3 ppm tolerance but still above EU and CODEX standards. Cooking soybeans in water, such as producing soymilk, can reduce CPF residues to 0.0 ppm, eliminating the pesticide. While heat treatments effectively reduced CPF in processed soybean products such as oil and soymilk, most soybeans are not consumed in whole-bean form. However, edamame, immature green soybeans, are an exception, as it is eaten directly after boiling or steaming. No studies specifically evaluated the impact of cooking or processing on CPF residues in edamame. This highlights a notable gap in available research and the need for further investigation to ensure the safety of edamame in relation to pesticide exposure.

VIII. Conclusion

Effectively reducing CPF residues in soybeans requires a combination of mitigation strategies combining naturally available and processing interventions. While storage time can

reduce CPF levels, residues still exceeded the MRL of 0.3 ppm across multiple studies, indicating that storage alone is insufficient in ensuring food safety. Storage must be supplemented by additional mitigation steps to achieve acceptable residue levels. The degradation of CPF by sunlight exposure demonstrates the potential for reducing CPF residues in soybeans. Under natural field conditions, CPF residues declined progressively across plant tissues to support the implementation of a 15-day preharvest dwell time. However, controlled laboratory experiments isolating the effects of solar and artificial UV radiation revealed far more rapid degradation. CPF residues degraded completely within 6 h of sunlight and 24 h of UVC short wavelength exposure, indicating a high susceptibility to light-induced breakdown when not shielded by plant surfaces or exposed to environmental variability. While artificial exposure studies provide insight into CPF's photolability, they may overestimate residue reduction in agricultural settings.

Among processing methods, washing with tap water while stirring removed up to 90% of residues after two washes, but the residue remained above the MRL. This method also involved soaking the soybeans, which could contribute to some CPF residue degradation; however, this factor was not analyzed independently. Further testing should follow on soaking and washing for proper understanding. O_3 treatment alone achieved reduction just above the MRL while preserving seed coat integrity, but its efficacy was limited by the shielding effect of oxidized residues. When combined with ULS, O_3 treatments became significantly more effective, reducing residues below 0.3 ppm within 20 minutes without damaging the seed coat, making this combination a promising postharvest strategy. CP treatment produced faster CPF degradation, but its intense surface etching caused unacceptable seed coat damage, limiting its suitability for intact food-grade soybeans. Thermal treatments, including roasting, boiling, and microwaving, consistently demonstrated CPF reductions, but these methods failed to reach below the MRL. These heat-based methods are particularly effective for processed soybean products such as oil and soymilk. However, most soybeans are not consumed whole, except edamame, which is typically eaten directly after steaming or boiling. Notably, none of the reviewed studies specifically examined CPF residue behavior in edamame, highlighting a critical gap in the literature. Given its direct human consumption with minimal processing, further research is needed to assess CPF mitigation strategies specific to edamame preparation. Overall, the review underscores the importance of combining mechanical, chemical, and thermal interventions to

ensure consumer safety. While several treatments successfully reduced CPF residues, no single method alone was sufficient across all scenarios. The synergistic use of O_3 and ULS, along with effective heat processing methods, offers the most practical and scalable options for reducing pesticide residues in soybeans without compromising product quality. Continued research, particularly on whole-bean products like edamame, and careful attention to evolving regulatory standards will be essential to protect public health and maintain consumer confidence in soy-based foods.

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