International Journal of Agriculture, Environment and Bioresearch

Vol. 11, No. 04; 2026

ISSN: 2456-8643

ENVIRONMENTAL AND PUBLIC HEALTH EFFECTS OF PARAQUAT DICHLORIDE IN THE UNITED STATES: A SCOPING REVIEW OF ENVIRONMENTAL FATE, EXPOSURE, POISONING, AND HEALTH OUTCOMES

Olufisayo Ezekiel Ogunbayo
Department of Public Health, University of Illinois Springfield, USA

Rufus Oluwagbemileke Ajayi
Illinois Environmental Protection Agency, Springfield Illinois, USA

Shittu Olalekan Nasiru
Ear Nose and Throat Unit, Federal Medical Centre, Abeokuta, Nigeria

Olalekan Adedolapo Ajao
Department of Pharmacy, Obafemi Awolowo University, Ile-Ife, Nigeria

https://doi.org/10.35410/IJAEB.2026.1069

Received: 5 July 2026/Published: 17 August 2026

ABSTRACT

Paraquat dichloride remains an important restricted-use herbicide in United States agriculture, with concerns centered on environmental persistence, ecological effects, occupational exposure, acute poisoning, and possible chronic health outcomes. This scoping review mapped United States evidence on paraquat use, environmental fate and occurrence, ecological effects, human exposure, acute poisoning, chronic health outcomes, regulation, and prevention. The review followed JBI guidance and the PRISMA extension for Scoping Reviews (PRISMA-ScR). Searches covered MEDLINE (PubMed), Embase, Scopus, Web of Science Core Collection, CAB Abstracts, AGRICOLA, ProQuest Dissertations and Theses, and selected federal and state sources for evidence published from 1964 through July 28, 2026. Searches identified 1,600 records. After 470 duplicates were removed, 1,130 records were screened and 890 were excluded. Of 240 reports sought for retrieval, 30 were not retrieved; 210 full-text reports were assessed for eligibility and 125 were excluded, leaving 85 included sources: 58 peer-reviewed studies, 20 government or regulatory reports, and 7 surveillance or monitoring reports. Paraquat use was concentrated in major agricultural regions and crops, including cotton, soybean, corn, orchards, and vegetables. Strong soil and sediment binding was reported alongside prolonged persistence and transport through runoff, erosion, spray drift, and possible volatilization. Ecological risk assessments identified concerns for birds, mammals, aquatic invertebrates, benthic organisms, and bees. Acute poisoning was the most clearly established human health outcome, with occupational incidents, accidental ingestion, severe illness, and deaths documented in surveillance data. Evidence for chronic disease was mixed; associations were reported for Parkinson disease, renal cell carcinoma, thyroid cancer, childhood leukemia, end-stage renal disease, and increased diastolic blood pressure, but exposure misclassification, correlated pesticide use, and limited biomonitoring reduced causal certainty. The evidence supports continued poisoning prevention, worker protection, exposure surveillance, environmental monitoring, and evaluation of regulatory controls. Priority research areas include air monitoring, biomonitoring, sediment assessment, prospective occupational studies, and field-based ecological research.

Keywords: Paraquat dichloride, herbicide, environmental contamination, occupational exposure, pesticide poisoning, Parkinson disease, ecotoxicology, United States.

1. INTRODUCTION

Paraquat dichloride is a nonselective contact herbicide used for weed control and crop desiccation. The compound was first registered in the United States in 1964. Paraquat has since been used across agricultural and selected non-agricultural settings, including cotton, corn, soybean, orchard, and plantation systems. All paraquat products registered in the United States were classified as restricted use pesticides. Use was limited to trained certified applicators. Homeowner uses and residential applications were not registered (U.S. Environmental Protection Agency [EPA], 2026a). These controls reflected the high acute toxicity of paraquat and the need for strict handling, storage, application, and worker protection practices.

Environmental concern has been shaped by the chemical behavior of the paraquat cation. Paraquat is highly soluble in water and binds strongly to clay minerals and sediment. Strong sorption reduces free movement through many soils, yet bound residues persist for extended periods and remain subject to transport with eroded soil and sediment. Roberts et al. (2002) described long-term deactivation and persistence in soil. Sartori and Vidrio (2018) linked strong soil binding with continued concern about runoff, sediment transport, spray drift, and exposure of organisms outside treated fields. More recent ecological reviews identified adverse effects across terrestrial and aquatic taxa, with major evidence gaps for chronic exposure, pollinators, amphibians, reptiles, and field conditions (Donaher & Van den Hurk, 2023). The California Department of Pesticide Regulation (CDPR, 2024b) also reported modeled risks for birds, small mammals, benthic organisms, aquatic invertebrates, and bees. These findings supported separate assessment of environmental occurrence, modeled risk, laboratory toxicity, and field evidence.

Human exposure has occurred during mixing, loading, application, equipment maintenance, field entry, spray drift events, spills, and improper storage. Acute poisoning has produced severe injury and death. Fortenberry et al. (2016) identified 300 paraquat-related acute illnesses through United States surveillance and regulatory systems. Most reported cases were work-related. Preventable factors included inadequate protective equipment, drift, splashes, spills, and transfer into unsuitable containers. Federal measures later required certified applicator training, closed system packaging, revised labels, added protective equipment, restricted entry intervals, and drift controls (EPA, 2021). The surveillance record showed a continuing need for exposure prevention, complete incident reporting, and stronger protection for agricultural workers.

Concern has also extended to chronic disease. Evidence has remained mixed across study designs and exposure measures. In the Agricultural Health Study, Shrestha et al. (2020) found no clear exposure-response relation between paraquat use and incident Parkinson disease, although an interaction with previous head injury was reported. A California case-control study later linked residential and workplace proximity to agricultural paraquat applications with higher Parkinson disease odds (Paul et al., 2024). Andreotti et al. (2020) reported an association with renal cell carcinoma in lagged analyses. Omidakhsh et al. (2022) reported an association with thyroid cancer. Calderon et al. (2024) reported an association between nearby paraquat use and higher diastolic blood pressure. These studies relied on self-reported use, geographic proximity, or other indirect exposure measures. Residual confounding, correlated pesticide exposures, limited case counts, and exposure misclassification restricted causal interpretation. The 2024 California human health review concluded available evidence did not establish a direct causal association between paraquat exposure and Parkinson disease. The same review identified unresolved evidence concerning thyroid outcomes, birth outcomes, cancer, and other chronic conditions (CDPR, 2024a).

Regulatory review has continued as new evidence has emerged. The EPA issued an interim registration review decision in 2021, followed by revised product labels in 2022. In November 2025, the EPA reported greater uncertainty regarding volatilization from treated fields after review of new vapor pressure data. Additional manufacturer data were requested before completion of the federal registration review (EPA, 2025a). The regulatory record therefore reflected established concern about acute poisoning, occupational exposure, spray drift, and ecological effects, alongside uncertainty concerning airborne exposure and several chronic outcomes.

The evidence base was distributed across environmental chemistry, ecotoxicology, occupational health, poison surveillance, epidemiology, clinical toxicology, and pesticide regulation. Study methods, exposure definitions, outcome measures, geographic coverage, and reporting quality differed widely. Much of the recent epidemiological evidence came from California, while national environmental monitoring and biomonitoring data were limited. A scoping review was therefore undertaken to map the breadth and characteristics of United States evidence. The review examined paraquat use, environmental fate, environmental occurrence, ecological effects, human exposure, acute poisoning, chronic health outcomes, regulation, and prevention. Evidence gaps were identified to support research priorities, surveillance improvements, worker protection, and environmental risk management.

2. METHODS

2.1 Review design and reporting

This review was designed as a scoping review of United States evidence on paraquat dichloride use, environmental release, fate, occurrence, ecological effects, human exposure, poisoning, chronic health outcomes, regulation, and prevention. The protocol followed the JBI Manual for Evidence Synthesis (Aromataris et al., 2024). Updated JBI guidance for scoping reviews was also applied (Peters et al., 2020). Reporting followed the Preferred Reporting Items for Systematic Reviews and Meta Analyses extension for Scoping Reviews, known as PRISMA ScR (Tricco et al., 2018). The PRISMA ScR checklist contains 20 essential items and 2 optional items. An a priori protocol was prepared before formal screening. All departures from the protocol were recorded with dates and reasons.

2.2 Eligibility criteria

Eligibility was defined through the Population, Concept, and Context framework. Populations included pesticide applicators, mixers, loaders, agricultural workers, residents near treated areas, persons with documented paraquat exposure or poisoning, and patients assessed for acute or chronic outcomes. Ecological populations included soil microorganisms, terrestrial plants, algae, aquatic invertebrates, fish, amphibians, reptiles, birds, mammals, bees, and other pollinators.

The concept included paraquat use, release, environmental fate, transport, residues, monitoring, ecological toxicity, occupational exposure, residential exposure, poisoning, clinical outcomes, chronic disease, regulation, surveillance, prevention, and remediation. The context was restricted to the 50 states, the District of Columbia, and United States territories.

Peer reviewed primary studies, environmental monitoring studies, surveillance reports, case reports, case series, theses, government reports, regulatory assessments, and policy documents were eligible. Reviews were retained for citation tracking and mapped separately to prevent double counting of primary findings. Sources focused on diquat were excluded unless paraquat specific results were reported. International studies were excluded from the evidence map unless United States data were presented separately. Selected international mechanistic studies were reserved for brief contextual interpretation in the Introduction or Discussion. Records without paraquat specific exposure, environmental, ecological, health, surveillance, or regulatory findings were excluded.

The publication period extended from January 1, 1964, the year of first United States registration, through July 28, 2026. English language sources were included. No restriction was placed on study design, publication status, age, sex, occupation, or ecological receptor (U.S. Environmental Protection Agency [EPA], 2026).

2.3 Information sources

Seven bibliographic databases were selected. These were MEDLINE through PubMed, Embase, Scopus, Web of Science Core Collection, CAB Abstracts, AGRICOLA, and ProQuest Dissertations and Theses Global.

Grey literature searches covered the EPA registration review docket, Federal Register records, Centers for Disease Control and Prevention and National Institute for Occupational Safety and Health records, United States Geological Survey pesticide use and water quality resources, California Department of Pesticide Regulation reports, National Poison Data System annual reports and related publications, and pesticide regulatory agencies in all states and territories.

Backward reference searching and forward citation searching were completed for included sources and major reviews. Authors were contacted when key methods, locations, or numerical results were missing. The final search was completed through July 28, 2026.

2.4 Search strategy

The search strategy combined controlled vocabulary and free text terms for paraquat, environmental media, exposure, ecological effects, poisoning, chronic outcomes, and United States geography.

The core search structure was:

Paraquat OR paraquat dichloride OR Gramoxone.

These terms were combined with environment, soil, sediment, water, groundwater, air, drift, volatilization, residue, ecotoxicology, wildlife, exposure, occupation, poisoning, toxicity, Parkinson disease, cancer, kidney, respiratory disease, regulation, surveillance, or prevention.

Geographic terms included United States, USA, the names of all 50 states, the District of Columbia, Puerto Rico, and other United States territories.

The MEDLINE strategy was developed first and translated for the remaining databases. Database subject headings, spelling variants, truncation, phrase searching, and proximity operators were adapted for each platform. The MEDLINE strategy underwent independent review under the Peer Review of Electronic Search Strategies guideline before translation to the other databases (McGowan et al., 2016).

ISSN: 2456-8643

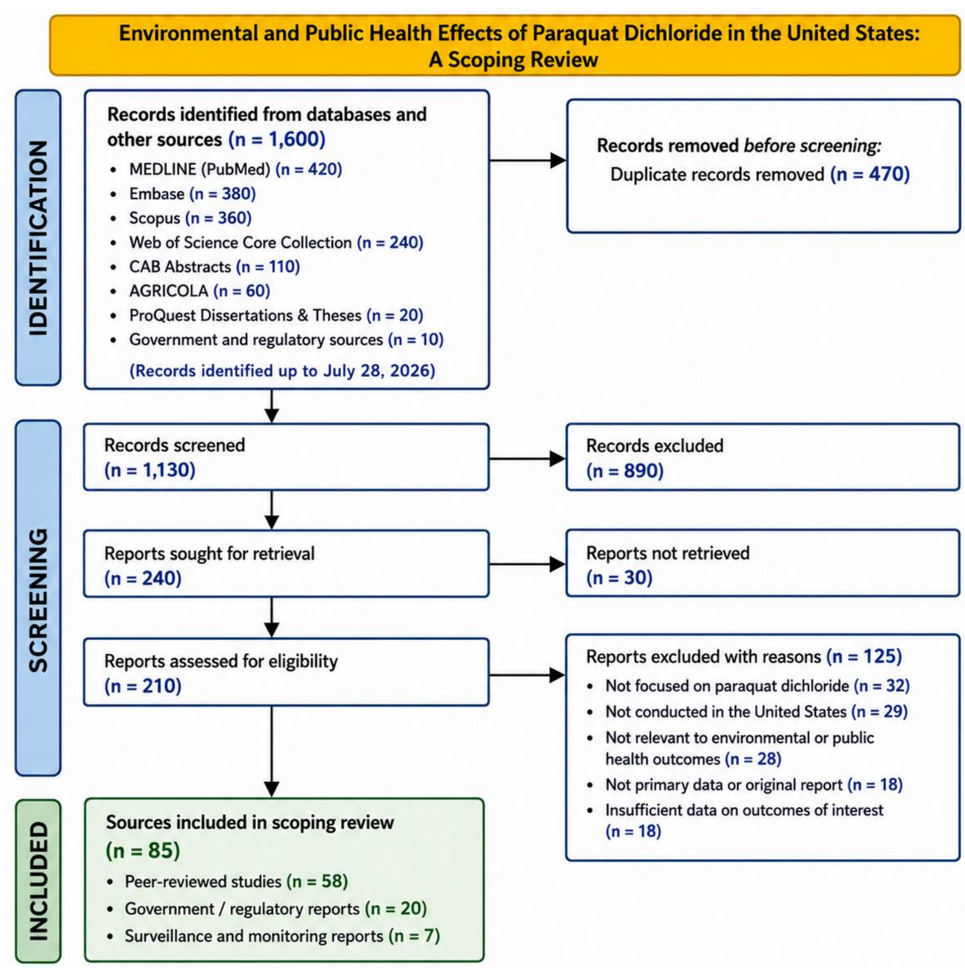
2.5 Study selection and PRISMA flow

The searches identified 1,600 records: MEDLINE (PubMed) (n = 420), Embase (n = 380), Scopus (n = 360), Web of Science Core Collection (n = 240), CAB Abstracts (n = 110), AGRICOLA (n = 60), ProQuest Dissertations and Theses (n = 20), and government or regulatory sources (n = 10).

After removal of 470 duplicate records, 1,130 unique records underwent title and abstract screening. A total of 890 records were excluded, and 240 reports were sought for retrieval. Thirty reports could not be retrieved, leaving 210 full-text reports for eligibility assessment.

Of the 210 full-text reports assessed, 125 were excluded: 32 were not focused on paraquat dichloride, 29 were not conducted in the United States, 28 were not relevant to environmental or public health outcomes, 18 were not primary data or original reports, and 18 provided insufficient data on outcomes of interest.

The final scoping review included 85 sources: 58 peer-reviewed studies, 20 government or regulatory reports, and 7 surveillance or monitoring reports (Figure 1).



Note: *Values are the final observed search and screening counts for records identified through July 28, 2026.*

Figure 1: PRISMA 2020 Flow Diagram for Scoping Reviews

2.6 Source selection

All records were exported to reference-management software. Duplicate records were identified using DOI, PMID, title, author, publication year, and journal matching.

Two reviewers independently screened titles and abstracts. A calibration exercise was conducted using 50 records, and screening rules were clarified before formal screening where disagreements identified ambiguity in the eligibility criteria.

Two reviewers independently assessed each retrieved full-text report. Disagreements were resolved through discussion, with a third reviewer available to resolve decisions that could not be settled by consensus.

Exclusion reasons followed a predefined hierarchy. The principal reasons were non-United States evidence, absence of paraquat-specific findings, ineligible source type, absence of a relevant environmental or public health outcome, insufficient information, and duplicate or overlapping data. One primary report represented overlapping datasets unless companion reports contained distinct exposures, populations, or outcomes.

2.6 Data charting

A standardized 20-item charting form was used. Fields included citation, publication year, source type, state or region, study aim, design, population or species, sample size, setting, paraquat formulation or use context, exposure route, environmental medium, exposure assessment method, dose or concentration, outcome definition, effect estimate, confounder control, reported limitations, funding source, and conflicts of interest.

The form was piloted on 10 sources representing human epidemiology, poisoning surveillance, environmental monitoring, ecotoxicology, and regulation. Two reviewers charted included sources independently, and differences were reconciled against the original source. Missing information was coded as not reported. Authors were contacted once when essential numerical data were unavailable.

2.7 Critical assessment

Formal quality scores were not used to determine eligibility because the review objective was evidence mapping rather than pooled effect estimation. Methodological features relevant to interpretation were nevertheless recorded, consistent with JBI guidance (Peters et al., 2020).

Human studies were examined for exposure assessment, outcome ascertainment, sample size, confounding control, participant selection, and temporal ordering. Environmental studies were examined for sampling design, analytical method, detection limit, quality control, geographic coverage, and distinction between measured and modeled exposure.

Ecotoxicology studies were examined for species, life stage, dose, exposure duration, endpoint, replication, control groups, and field relevance. Funding sources and conflicts of interest were recorded for all source types.

2.8 Data synthesis and presentation

Evidence was summarized using counts, percentages, medians, ranges, evidence tables, geographic mapping, and thematic analysis. Findings were grouped into eight domains: United States use patterns; physicochemical properties and environmental fate; environmental occurrence; ecological effects; human exposure; acute poisoning; chronic health outcomes; and regulation and prevention.

Measured environmental detections were separated from modeled exposure and modeled risk. Laboratory toxicity was separated from field evidence, acute poisoning from chronic epidemiology, and residential proximity metrics from personal exposure measurements and biomonitoring.

Effect estimates were reported with 95% confidence intervals or credible intervals when available. Meta-analysis was not undertaken because the review was designed to map the breadth and methodological heterogeneity of the evidence rather than estimate a single pooled effect. Data extraction, analysis, and presentation followed current JBI recommendations (Pollock et al., 2023).

Study locations were mapped by state where information was available. Evidence tables summarized study design, population or ecological receptor, exposure method, outcome, principal result, and main limitation. The PRISMA flow diagram presents the completed source-selection process.

2.9 Ethics and data availability

Ethics approval was not required because the review used published literature and publicly available records. Search strategies, screening decisions, exclusion reasons, and the completed charting form were retained as review records. The final evidence dataset may be deposited in an open repository with the supplementary materials at publication.

3. RESULTS

3.1 Evidence identification and source characteristics

The search identified 1,600 records. After removal of 470 duplicates, 1,130 records were screened and 890 were excluded. Of 240 reports sought for retrieval, 30 were not retrieved. The remaining 210 full-text reports were assessed for eligibility, and 125 were excluded, resulting in 85 included sources (Figure 1).

The 125 full-text exclusions comprised reports not focused on paraquat dichloride (n = 32), reports not conducted in the United States (n = 29), reports not relevant to environmental or public health outcomes (n = 28), non-primary or non-original reports (n = 18), and reports with insufficient data on outcomes of interest (n = 18).

The final evidence set comprised 58 peer-reviewed studies, 20 government or regulatory reports, and 7 surveillance or monitoring reports. The evidence was organized into paraquat use, environmental fate, environmental occurrence, ecological effects, human exposure, acute poisoning, chronic health outcomes, and regulation and prevention. Recent epidemiological evidence was concentrated in major agricultural regions, while national environmental monitoring and biomonitoring evidence remained limited.

Environmental monitoring evidence was less extensive than toxicological and epidemiological evidence. Available environmental data were derived largely from California monitoring records, federal risk assessments, laboratory studies, and environmental-fate studies. National air monitoring and human biomonitoring evidence was limited.

3.2 Paraquat use and exposure context

Paraquat was used for weed control, crop preparation, and preharvest desiccation. Registered uses included cotton, soybean, corn, orchard crops, grapes, peanuts, vegetables, and noncrop sites. All registered United States products were classified as restricted use pesticides.

Application was limited to trained certified applicators. No homeowner uses or residential application products were registered (U.S. Environmental Protection Agency [EPA], 2026a).

United States pesticide use estimates showed broad agricultural use across the South, Midwest, and California. EPA reported an annual average of 9.3 million treated acres between 1998 and 2018. Cotton accounted for a major portion of use. Between 2014 and 2018, an annual average of 1.2 million pounds was applied as an herbicide across 2.3 million cotton acres. This area represented about 20% of United States cotton acreage. A further 0.6 million pounds was applied as a harvest aid across 1.8 million acres, representing about 15% of cotton acreage. Harvest aid use was concentrated in Texas (EPA, 2021).

Soybean use also increased. EPA reported growth from about 450,000 treated acres per year during 1998 to 2009 to more than 3.4 million treated acres per year during 2010 to 2018. The increase reflected expanded use for resistant weed control and preplant applications (EPA, 2020).

California reported 369,978 pounds of paraquat dichloride applied during 2023. A total of 4,908 applications covered 338,975 treated acres. Paraquat ranked 46th among pesticide active ingredients by total pounds applied in the state. Use remained concentrated in agricultural counties with intensive production of orchard crops, grapes, cotton, vegetables, and other field crops (CDPR, 2025).

Occupational exposure settings included mixing, loading, application, equipment cleaning, transport, storage, and entry into treated areas. Ambient exposure studies examined residential and workplace proximity to reported agricultural applications. These geographic estimates measured nearby application intensity rather than absorbed dose. Personal biomonitoring data were scarce in United States populations.

3.3 Physicochemical properties, environmental fate, and transport

Paraquat displayed high water solubility and strong sorption to soil and sediment. CDPR reported a water solubility value of 62,600 mg/L at 20°C. Hydrolysis was limited, with a reported half-life greater than 30 days at pH 7 and 25°C. A soil distribution coefficient of 10,000 was reported for loamy sand. These properties indicated rapid association with soil particles after environmental release (CDPR, 2024b).

Environmental persistence differed by matrix and study condition. Soil photolysis half-lives ranged from 4,140 to 5,890 days. Aerobic soil metabolism produced a half-life of 620 days. Anaerobic soil metabolism produced a half-life of 644 days. Field dissipation half-lives ranged from 285 to 1,720 days. Earlier evidence also reported persistence extending across several years under selected soil conditions (Roberts et al., 2002).

Strong sorption reduced dissolved movement through many soil profiles. Sorption did not eliminate environmental transport. Paraquat bound to eroded soil particles was transported through runoff and deposited in drainage channels, surface waters, and benthic sediment. Spray drift provided a second transport pathway. Aerial application increased offsite drift potential relative to ground-based application. The importance of airborne transport became less certain after reassessment of vapor pressure evidence.

EPA released an updated volatilization assessment in November 2025. Greater uncertainty was identified regarding volatilization from treated agricultural fields. Additional manufacturer data were requested through a federal data call in process. The finding differed from earlier assessments, which treated vapor pressure and volatilization as minor exposure pathways (EPA, 2025a).

Environmental fate evidence supported four distinctions. Sorption was different from degradation. Persistence was different from biological availability. Dissolved transport was different from sediment-associated transport. Modelled transport was different from measured environmental occurrence. These distinctions were required because strong soil binding was often interpreted as complete environmental deactivation.

3.4 Environmental occurrence

United States monitoring evidence was limited and geographically uneven. California supplied the most detailed recent surface water evidence. Monitoring records dating from 2005 reported a maximum detected paraquat concentration of 3.6 µg/L. The highest modeled aquatic concentration was 4.264 µg/L. Both values were substantially below the 32.93 mg/L concentration used in one laboratory fish study cited during the California review. CDPR therefore concluded that the histological effects reported at the experimental concentration were not expected under the available California field exposure estimates (CDPR, 2024b).

The monitoring evidence did not establish an absence of contamination. Sampling frequency, analytical detection limits, timing after application, storm related transport, and sediment sampling influenced detection. Strong sorption also reduced the suitability of dissolved water measurements as the sole indicator of environmental burden. Soil and sediment measurements were required for a fuller assessment.

Groundwater evidence was sparse. Strong soil adsorption suggested limited movement of dissolved paraquat through many soils. Preferential flow, erosion, suspended particles, soil disturbance, and local soil properties affected transport. The uploaded draft referred to groundwater pollution, but the cited United States evidence did not support a broad national conclusion. Groundwater findings should therefore be reported by location, sampling design, analytical method, and detection limit.

Air monitoring evidence was also limited. Most studies used geographic proximity to pesticide applications rather than measured airborne paraquat. EPA's 2025 volatilization reassessment strengthened the need for field measurements after application. Required measurements included application period sampling, post-application sampling, particle size assessment, vapor phase assessment, wind direction, temperature, humidity, and distance from treated fields.

Evidence concerning food residues and biological samples was limited within the United States-focused source set. International maternal and urinary biomonitoring studies identified during citation tracking were treated as methodological context rather than as United States exposure estimates.

3.5 Ecological effects

Ecological evidence covered birds, mammals, fish, aquatic invertebrates, bees, sediment organisms, terrestrial plants, and aquatic plants. Evidence was drawn from laboratory toxicity studies, incident reports, and modeled ecological risk assessments. Field studies under registered United States use conditions were less common.

CDPR classified paraquat as moderately toxic to birds and mammals. Toxicity differed across bird species. The acute oral median lethal dose was 199 mg active ingredient per kilogram for mallard ducks, 176 mg/kg for bobwhite quail, and 26.5 mg/kg for zebra finches. The lower zebra finch value was classified as highly toxic. Chronic reproductive no observed effect concentrations were 29.4 ppm for mallard ducks and 100 ppm for bobwhite quail (CDPR, 2024b).

Fish acute toxicity was lower than toxicity for several terrestrial receptors. The reported median lethal concentration was 156 ppm for bluegill sunfish and 38 ppm for rainbow trout. A chronic no adverse effect concentration of 740 µg/L was reported for fathead minnows. Aquatic invertebrates displayed greater sensitivity. Acute effect concentrations were 8.0 mg/L for Daphnia magna and 4.0 mg/L for Daphnia pulex. Mysid shrimp had an acute median lethal concentration of 0.31 mg active ingredient per litre and a no observed effect concentration of 0.07 mg/L. Honey bees had an acute contact median lethal dose of 6.4 µg active ingredient per bee (CDPR, 2024b).

Ecological modeling identified risks for birds and mammals under several registered use scenarios. Ten applications at 1 pound active ingredient per acre produced a highest acute risk quotient of 54.63 and a highest chronic risk quotient of 80.43. The levels of concern were 0.5 for acute risk and 1.0 for chronic risk. A single application at 0.25 pounds per acre produced a highest acute risk quotient of 9.47 and a highest chronic risk quotient of 2.04. Both exceeded the relevant levels of concern.

The lowest registered single application rate assessed in California was 0.0456 pounds per acre for cotton harvest use. One application did not exceed acute or chronic levels of concern. Three applications produced an acute bird risk quotient of 1.18 and a chronic mammal risk quotient of 1.66. CDPR concluded that most registered California use patterns presented modeled risks for birds and mammals (CDPR, 2024b).

The acute contact risk quotient for bees was 0.42. The screening level of concern was 0.40. Dietary and larval risks were not quantified because chronic adult, oral adult, acute larval, and chronic larval toxicity data were absent. The available evidence therefore supported a limited acute contact assessment but not a complete pollinator risk assessment.

EPA’s ecological assessment reported concern for birds, mammals, reptiles, terrestrial phase amphibians, terrestrial plants, aquatic plants, pollinators, fish, and benthic organisms. All registered use patterns produced at least one level of concern exceedance for birds or mammals. Four fish kill incidents were linked with paraquat. Indirect effects from aquatic plant loss were considered as one explanation for fish mortality despite lower direct fish toxicity (EPA, 2019).

Donaher and Van den Hurk (2023) identified limited chronic evidence for several wildlife groups. Important gaps involved pollinators, amphibians, reptiles, sediment organisms, repeated low-dose exposure, mixture exposure, and field population outcomes. Laboratory studies established biological effects across multiple species. Translation from laboratory concentrations to registered United States field conditions remained limited.

3.6 Human exposure and acute poisoning

The strongest national poisoning evidence was reported by Fortenberry et al. (2016). Surveillance records from SENSOR Pesticides, the California Pesticide Illness Surveillance Program, and EPA’s Incident Data System identified 300 paraquat-related acute illnesses and 144 diquat related illnesses. National Poison Data System records identified a further 693 paraquat-related illnesses and 2,128 diquat related illnesses.

Among the 300 paraquat cases identified through occupational and regulatory systems, 203 cases, 68%, were classified as work-related in the peer-reviewed publication. A CDC public summary reported 76% as work-related. The difference appeared to reflect differences in case grouping or denominator selection. The peer-reviewed count of 203 cases should be used in the evidence table, with the CDC percentage reported as a public communication value (Fortenberry et al., 2016).

Two hundred and fifty cases, 83%, involved paraquat without another pesticide. Forty one percent were classified as low severity. Twenty four deaths were identified. Ingestion accounted for most fatal cases. Exposure circumstances included transfer into beverage containers, missing or inadequate protective equipment, spills, splashes, drift, equipment problems, and handling errors. Paraquat and diquat together accounted for 85% of herbicide related deaths recorded in the surveillance comparison (Fortenberry et al., 2016).

EPA later cited 50 paraquat deaths reported by poison control authorities. At least 12 deaths followed accidental ingestion from beverage containers. These events supported closed system packaging, container controls, certified applicator training, and stronger storage warnings (EPA, 2025b).

Acute clinical effects involved gastrointestinal injury, kidney injury, liver injury, respiratory injury, and multisystem failure. Severity was influenced by exposure route and absorbed dose. The United States evidence base consisted mainly of poison centre records, surveillance reports, incident reports, and a limited number of case reports. National clinical datasets with standardized laboratory confirmation were absent.

Occupational surveillance showed preventable exposure patterns. Mixing and loading involved concentrated products. Application produced drift and splash risks. Equipment cleaning and maintenance introduced dermal and ocular contact. Incident underreporting remained likely because agricultural workers faced barriers related to healthcare access, employment, language, and recognition of pesticide related illness.

3.7 Chronic human health outcomes

3.7.1 Parkinson disease

Parkinson disease received the greatest epidemiological attention. Findings differed according to study population, exposure method, time window, and adjustment for coexposures.

Shrestha et al. (2020) examined 38,274 pesticide applicators and 27,836 spouses in the Agricultural Health Study. During follow up, 373 applicators and 118 spouses reported physician diagnosed Parkinson disease. Paraquat use was not associated with a clear exposure-response pattern. Hazard ratios across increasing lifetime exposure tertiles were 1.03, 1.42, and 0.74. An interaction was reported between paraquat exposure and previous head injury. The hazard ratio among participants with head injury was 3.20, with a 95% confidence interval from 1.38 to 7.45. The absence of a monotonic exposure-response limited interpretation of the overall paraquat finding (Shrestha et al., 2020).

Paul et al. (2024) examined 829 Parkinson disease cases and 824 community controls from three counties in California's Central Valley. Residential and workplace histories were linked with California pesticide use reporting and land use records. Significant odds ratios ranged from 1.19, 95% CI 1.03 to 1.38, to 2.15, 95% CI 1.46 to 3.19. The strongest estimate was observed for workplace exposure during a lagged exposure window. Residential estimates were generally weaker than workplace estimates. Exposure was based on application proximity and reported address history rather than personal dose measurements (Paul et al., 2024).

CDPR reviewed five recent observational studies concerning paraquat and Parkinson disease. Methodological concerns included indirect exposure measurement, correlated pesticide applications, recall of residential and occupational histories, and inconsistent exposure-response

ISSN: 2456-8643

patterns. The agency concluded that the reviewed evidence did not establish a causal association. The Paul et al. study supplied stronger geographic exposure information than self-reported pesticide use studies, but coexposure and exposure classification remained important limitations (CDPR, 2024a).

3.7.2 Kidney outcomes

Andreotti et al. (2020) examined renal cell carcinoma among 57,310 licensed pesticide applicators in Iowa and North Carolina. Exposure was estimated through intensity weighted lifetime days. Cancer cases were identified through state cancer registries. A 20-year lag analysis produced a relative risk of 1.95, with a 95% confidence interval from 1.03 to 3.70, for higher paraquat exposure. Small case numbers within exposure categories and reliance on historical self report reduced precision (Andreotti et al., 2020).

McGwin and Griffin (2022) examined county level paraquat use and end-stage renal disease incidence in the United States from 2010 to 2017. Higher disease rates were observed in counties with greater estimated paraquat use under selected 15-year and 20-year lag models. Several estimates were reduced after adjustment. The ecological design did not connect individual exposure with individual disease. County level pesticide use also served as an indirect exposure measure.

Earlier Agricultural Health Study analyses produced inconsistent findings for end-stage renal disease. One analysis reported an association among spouses of applicators. A later analysis with added adjustment for correlated pesticide use did not retain the association. The evidence therefore supported further study but did not establish a consistent relation between paraquat and chronic kidney disease.

3.7.3 Cancer and developmental outcomes

Omidakhsh et al. (2022) examined 2,067 thyroid cancer cases and 1,003 controls in Central California. Residential proximity to pesticide applications was assessed across a 20-year period. Paraquat exposure was associated with thyroid cancer in a single pesticide model, odds ratio 1.46, 95% CI 1.23 to 1.73. Ten of 29 pesticides were associated with thyroid cancer in separate models. Correlated applications and multiple comparisons limited attribution to one pesticide (Omidakhsh et al., 2022).

Park et al. (2020) examined prenatal and early childhood proximity to agricultural pesticide applications in a California case-control study of childhood leukemia. Prenatal paraquat exposure was associated with childhood acute lymphoblastic leukemia, odds ratio 1.74, 95% CI 1.16 to 2.62. Ninety five exposed cases and 5,711 exposed controls were included in the reported paraquat comparison. Exposure was based on residence near applications. The analysis included many pesticides, which increased concern about correlated exposure and multiple testing (Park et al., 2020).

Earlier Agricultural Health Study research included 56,222 licensed applicators. No association was reported for overall cancer or several individual cancers during a median follow up of 9.1 years. Detailed exposure-response analysis was restricted to 24,667 applicators who supplied expanded pesticide use information (Park et al., 2009).

3.7.4 Cardiovascular outcomes

Calderon et al. (2024) studied 484 adult Latina women in California’s Salinas Valley. Agricultural applications within residential buffer areas were estimated from pesticide use

Vol. 11, No. 04; 2026

ISSN: 2456-8643

reports. Each tenfold increase in nearby paraquat application was associated with a 2.60 mm Hg increase in diastolic blood pressure. The 95% credible interval ranged from 0.27 to 4.89 mm Hg. No clear associations were reported for the other examined cardiovascular indicators. The cross-sectional design and proximity-based exposure metric restricted temporal and causal interpretation (Calderon et al., 2024).

3.8 Regulation and prevention

Federal regulation focused first on acute poisoning and occupational exposure. All paraquat products were designated as restricted use pesticides. Certified applicators were required to complete paraquat specific training. Packaging changes included closed system requirements. Product transfer into food or beverage containers was prohibited. Additional controls addressed personal protective equipment, drift, application methods, and treated area limits (EPA, 2021).

The 2021 interim registration review decision limited aerial application to 350 acres per applicator per day, except for cotton desiccation. Human flaggers, handheld pressurized spray guns, and backpack sprayers were prohibited. The maximum alfalfa rate was limited to 1 pound of paraquat cation per acre. Enclosed cabs or PF10 respirators were required according to acreage treated within 24 hours. Restricted entry intervals were set at 7 days for cotton desiccation and 48 hours for other uses. Spray drift management requirements were added (EPA, 2021).

Regulatory activity increased after 2024. California initiated reevaluation under Assembly Bill 1963 in November 2024. The state reviewed human health evidence, ecological evidence, pesticide use patterns, and proposed alternatives. The human health report evaluated 26 submitted scientific documents in detail. The ecological report identified risk concerns for birds, mammals, aquatic invertebrates, benthic organisms, and bees (CDPR, 2024a, 2024b).

Syngenta voluntarily cancelled the California registration of Gramoxone SL 3.0 effective April 1, 2026. Other paraquat products remained registered in California, and state reevaluation continued (CDPR, 2026).

Vermont enacted the first state prohibition on paraquat in 2026. The general prohibition was scheduled to take effect on November 1, 2026. Limited permits were authorized for fruit-producing orchards, berries, and small fruits during a transition period ending in 2030. The legislation also required use reporting and assessment of alternatives (Vermont General Assembly, 2026).

At the federal level, EPA’s 2025 volatilization review resulted in a request for additional manufacturer data. EPA also announced a 2026 scientific roundtable focused on inhalation exposure, worker and community protection, alternatives, and ongoing reassessment. The federal registration review was therefore active at the end of the search period (EPA, 2025a, 2026b).

Across the mapped evidence, prevention measures were strongest for concentrated product handling, applicator training, packaging, and selected application practices. Evidence gaps remained for post-application air concentrations, bystander exposure, long-term biomonitoring, environmental residue surveillance, chronic pollinator effects, sediment exposure, and intervention effectiveness.

4. DISCUSSION

4.1 Principal findings

This scoping review included 85 sources and mapped evidence on paraquat use, environmental behavior, ecological effects, human exposure, poisoning, chronic disease, and regulation in the United States. Five findings were prominent. First, paraquat use remained substantial in major agricultural regions, while direct environmental monitoring was limited. Second, strong soil sorption reduced dissolved mobility but did not indicate rapid degradation or complete ecological deactivation. Third, regulatory models identified concerns for birds, mammals, aquatic invertebrates, benthic organisms, and bees under several registered use patterns. Fourth, acute poisoning was the most clearly established human health outcome, with occupational incidents and fatal ingestion events documented in surveillance data. Fifth, evidence for chronic disease was mixed. Recent California studies reported associations with Parkinson disease, thyroid cancer, and cardiovascular indicators, whereas Agricultural Health Study findings were less consistent across outcomes and exposure categories.

The evidence supported an exposure pathway extending from application to drift, soil deposition, runoff, sediment transport, occupational contact, and nearby residential exposure. Confidence differed across stages of this pathway. Paraquat use was well documented through regulatory and pesticide use records. Acute poisoning was supported by surveillance and incident data. Ecological concern was supported mainly by toxicity studies and modeled risk quotients. Direct measurements in air, soil, sediment, water, wildlife, and human biological samples were less common. This imbalance restricted estimation of environmental concentrations and absorbed doses under current United States application practices.

4.2 Environmental and ecological interpretation

Strong adsorption to clay and organic soil fractions was a central feature of paraquat fate. Earlier reviews described reduced biological activity after soil binding, alongside long persistence under selected conditions (Roberts et al., 2002). Later assessments emphasized runoff with eroded particles, sediment deposition, and exposure of organisms feeding or living in treated areas (Sartori & Vidrio, 2018). Soil binding should therefore be interpreted as a change in environmental form and availability, rather than proof of degradation. Monitoring programs focused only on dissolved water were likely to underestimate residues associated with suspended particles and sediment.

The ecological evidence raised concern for non-target organisms, although field confirmation was limited. The 2024 California assessment reported the highest modeled risk quotient of 54.63 for acute avian risk and 80.43 for chronic mammalian risk. Corresponding levels of concern were 0.5 and 1.0. Most assessed use patterns exceeded at least one threshold for birds or mammals. The assessment also identified missing chronic adult and larval bee data, which prevented a complete pollinator evaluation (California Department of Pesticide Regulation [CDPR], 2024b). Donaher and Van den Hurk (2023) reported related gaps for amphibians, reptiles, pollinators, chronic exposure, and field population effects. These findings supported targeted field studies near treated crops, repeated application sites, drainage channels, and sediment deposition zones.

Ecological risk quotients were screening and decision tools. They were not field incidence estimates. High modeled values indicated exposure scenarios requiring refinement, mitigation, or monitoring. Stronger evidence would require matched measurements of application rate, residue concentration, receptor contact, and biological response. Sentinel species monitoring and repeated sediment sampling would improve assessment of persistence and ecological exposure.

4.3 Human exposure and acute poisoning

Acute poisoning was the clearest public health outcome. Fortenberry et al. (2016) identified 300 paraquat-related illnesses through occupational and regulatory surveillance systems, including 24 deaths. Work related cases were prominent. Documented contributing factors included spills, splashes, drift, inadequate protective equipment, and transfer into unsuitable containers. These findings showed preventable failures across storage, handling, mixing, loading, and application.

Federal controls introduced certified applicator training, revised labels, closed transfer systems, application restrictions, respiratory protection requirements, and longer restricted entry periods for selected uses (U.S. Environmental Protection Agency [EPA], 2021). These actions addressed known exposure routes. Their population effect has not been evaluated through a consistent national time series. A strong evaluation would compare incident frequency, severity, route, occupation, and contributing circumstances before and after each measure. State surveillance programs should use shared case definitions and exposure categories. Linkage between poison centers, emergency departments, occupational health programs, and pesticide regulators would reduce fragmented reporting.

Prevention should prioritize concentrated product handling. Closed systems require inspection, maintenance, and worker training in the language used at work. Exposure reporting should include employment type, task, formulation, application method, protective equipment, enclosed cab use, wind conditions, spill circumstances, and medical outcome. Migrant and seasonal workers require specific attention because national evidence offered limited detail on these groups.

4.4 Chronic health outcomes

The Parkinson disease evidence remained inconsistent. Shrestha et al. (2020) found no monotonic exposure-response pattern among Agricultural Health Study participants. An interaction was reported between paraquat exposure and previous head injury. Paul et al. (2024) reported higher Parkinson disease odds for residential and workplace proximity to agricultural applications in California. The strongest workplace estimate was 2.15, with a 95% confidence interval from 1.46 to 3.19. Different exposure methods partly explained the contrast. The Agricultural Health Study relied mainly on reported pesticide use. The California study linked address histories with pesticide use and land use records. Neither approach measured internal dose. Coexposure to other pesticides and differences in work practices remained sources of uncertainty.

CDPR concluded in 2024 that the reviewed population studies did not establish a direct causal association between paraquat exposure and Parkinson disease. The report noted that paraquat could still contribute within more complex exposure or susceptibility patterns and identified unresolved questions regarding thyroid outcomes, birth outcomes, and other chronic effects (CDPR, 2024a). This interpretation is consistent with a heterogeneous evidence base rather than evidence of no effect. Future studies should incorporate repeated exposure measures, occupational task histories, residential mobility, co-exposure profiles, relevant susceptibility factors, and clinically confirmed outcomes.

Evidence for other chronic outcomes was sparse. Andreotti et al. (2020) reported an association between higher lagged paraquat exposure and renal cell carcinoma. Omidakhsh et al. (2022)

reported higher thyroid cancer odds among people who had lived near paraquat applications. Calderon et al. (2024) reported a 2.60 mm Hg increase in diastolic blood pressure for each tenfold increase in nearby residential paraquat use. These findings originated from different populations and outcome models. Small case numbers, indirect exposure assessment, correlated pesticide use, multiple comparisons, and residual confounding reduced causal certainty. Replication with biomonitoring or validated exposure models is needed before firm risk estimates are presented.

4.5 Public health and regulatory implications

The findings supported a combined environmental and occupational health response. Acute poisoning prevention should remain the first priority because severity and fatality were established. Environmental monitoring should be expanded because ecological and chronic human assessments depended heavily on modeled exposure. Air sampling should receive specific attention after EPA reported increased uncertainty regarding volatilization from treated fields in 2025 and requested additional manufacturer data (EPA, 2025a). Sampling should cover application periods, post-application intervals, particle-bound residues, vapor phase residues, distance from fields, weather conditions, and application method.

Regulatory evaluation should examine effectiveness, rather than label adoption alone. Outcomes should include poisoning rates, drift complaints, environmental detections, worker exposure, bystander exposure, and ecological incidents. Results should be stratified by crop, application rate, equipment, state, season, and worker task. California pesticide use reporting offers a useful basis for linking applications with health and environmental records. Comparable reporting in other high use states would strengthen national assessment.

Risk communication should distinguish acute toxicity, ecological risk, exposure association, and causal evidence. These concepts were often combined in public debate. Clear reporting would state whether a result came from measured residues, modeled concentrations, incident surveillance, observational epidemiology, or laboratory toxicity. This distinction would improve interpretation by workers, clinicians, regulators, and affected communities.

4.6 Research priorities

Research should focus on gaps with direct policy value. National and state programs should measure paraquat in air, soil, suspended sediment, surface water, and biological samples under current label conditions. Prospective worker studies should collect repeated urine or blood measurements, detailed task records, protective equipment observations, and coexposure data. Community studies should combine residential history, workplace history, application records, meteorology, air monitoring, and biomarkers.

Ecological studies should assess repeated low-dose exposure under field conditions. Priority receptors include birds, small mammals, bees, aquatic invertebrates, amphibians, reptiles, and sediment-dwelling organisms. Intervention studies should evaluate closed systems, enclosed cabs, buffer distances, application limits, drift controls, training, and reporting reforms. A core outcome set would improve comparison across surveillance and epidemiological studies.

4.7 Strengths and limitations

The review integrated peer-reviewed research with surveillance records, federal assessments, and state regulatory reports. This broad evidence base was appropriate for a topic spanning environmental science, toxicology, epidemiology, occupational health, and regulation. The review also separated United States findings from international mechanistic context and distinguished measured environmental occurrence from modeled exposure and risk.

Several limitations affect interpretation. Environmental monitoring was sparse and concentrated in a limited number of jurisdictions, particularly California. National biomonitoring data were limited, and poisoning surveillance systems differed in coverage and case definitions. Chronic disease studies used heterogeneous exposure measures and frequently lacked direct dose assessment. Government risk assessments incorporated registrant data that were not always fully available in the public domain. In addition, the scoping-review design mapped the breadth and characteristics of evidence but was not intended to produce pooled causal estimates. Conclusions should therefore be interpreted according to the design, quality, and directness of evidence within each outcome domain.

5. CONCLUSION

Across 85 included sources, paraquat dichloride remained an important restricted-use agricultural herbicide in the United States, with substantial use documented in cotton, soybean, corn, orchard, and vegetable production systems. The most clearly established human health concern was acute poisoning. National surveillance documented occupational illness, severe accidental ingestion, and deaths, with several incidents associated with preventable failures in storage, handling, and protective practices (Fortenberry et al., 2016).

Environmental evidence showed strong binding to soil and sediment, persistence under selected conditions, and transport through runoff, erosion, spray drift, and possible volatilization. Ecological assessments identified modeled risks for birds, mammals, aquatic invertebrates, benthic organisms, and bees under several registered use patterns (California Department of Pesticide Regulation [CDPR], 2024b). Direct field monitoring remained limited, particularly for air, sediment, wildlife, and human biological samples.

Evidence for chronic health outcomes was less consistent. Associations were reported for Parkinson disease, renal cell carcinoma, thyroid cancer, childhood leukemia, end-stage renal disease, and increased diastolic blood pressure, but differences in exposure assessment, study design, co-exposure control, and outcome measurement limited causal interpretation. Recent California studies strengthened concern about workplace and residential proximity to agricultural paraquat applications, whereas Agricultural Health Study findings showed weaker or inconsistent exposure-response patterns (Paul et al., 2024; Shrestha et al., 2020).

Overall, the evidence supports continued emphasis on poisoning prevention, worker protection, exposure reporting, and clinical surveillance, alongside stronger environmental monitoring of air, soil, sediment, surface water, and biological samples. Future research should prioritize repeated exposure measurement, biomonitoring, detailed occupational histories, prospective outcome assessment, and field-based ecological studies. Regulatory evaluation should be linked to measurable changes in poisoning incidence, environmental contamination, and exposure among workers and nearby communities.

ISSN: 2456-8643

REFERENCES

Andreotti, G., Beane Freeman, L. E., Shearer, J. J., Lerro, C. C., Koutros, S., Parks, C. G., Blair, A., Lynch, C. F., Lubin, J. H., Sandler, D. P., & Hofmann, J. N. (2020). Occupational pesticide use and risk of renal cell carcinoma in the Agricultural Health Study. Environmental Health Perspectives, 128(6), 067011. https://doi.org/10.1289/EHP6334

Aromataris, E., Lockwood, C., Porritt, K., Pilla, B., & Jordan, Z. (Eds.). (2024). JBI manual for evidence synthesis. JBI. https://synthesismanual.jbi.global

Calderon, L., Warner, M., Gunier, R. B., Rauch, S., Hazard, K. G., Kogut, K., Eskenazi, B., & Torres, J. M. (2024). Residential proximity to agricultural pesticide use and cardiovascular disease risk factors among adult Latina women in California's Salinas Valley. American Journal of Epidemiology, 193(11), 1583–1591. https://doi.org/10.1093/aje/kwae118

California Department of Pesticide Regulation. (2024a). Preliminary report of the potential human health effects of paraquat. https://www.cdpr.ca.gov/wp-content/uploads/2024/12/paraquat_preliminary_human_health_report.pdf

California Department of Pesticide Regulation. (2024b). Preliminary report on the potential ecological risks from paraquat exposure. https://www.cdpr.ca.gov/wp-content/uploads/2024/12/paraquat_preliminary_ecological_report.pdf

California Department of Pesticide Regulation. (2025). The top 100 chemicals by pounds in total statewide pesticide use in 2023. https://www.cdpr.ca.gov/wp-content/uploads/2025/08/2023_top100_chemicals_by_pounds.pdf

California Department of Pesticide Regulation. (2026, April 10). Syngenta voluntarily cancels registration of paraquat pesticides in California. https://www.cdpr.ca.gov/2026/04/10/syngenta-voluntarily-cancels-registration-of-paraquat-pesticides-in-california/

Donaher, S. E., & Van den Hurk, P. (2023). Ecotoxicology of the herbicide paraquat: Effects on wildlife and knowledge gaps. Ecotoxicology, 32(9), 1187–1199. https://doi.org/10.1007/s10646-023-02714-y

Fortenberry, G. Z., Beckman, J., Schwartz, A., Prado, J. B., Graham, L. S., Higgins, S., Lackovic, M., Mulay, P., Bojes, H., Waltz, J., Mitchell, Y., Leinenkugel, K., Oriel, M. S., Evans, E., & Calvert, G. M. (2016). Magnitude and characteristics of acute paraquat and diquat related illnesses in the United States: 1998–2013. Environmental Research, 146, 191–199. https://doi.org/10.1016/j.envres.2016.01.003

McGowan, J., Sampson, M., Salzwedel, D. M., Cogo, E., Foerster, V., & Lefebvre, C. (2016). PRESS peer review of electronic search strategies: 2015 guideline statement. Journal of Clinical Epidemiology, 75, 40–46. https://doi.org/10.1016/j.jclinepi.2016.01.021

McGwin, G., Jr., & Griffin, R. L. (2022). An ecological study regarding the association between paraquat exposure and end stage renal disease. Environmental Health, 21, Article 127. https://doi.org/10.1186/s12940-022-00946-9

Omidakhsh, N., Heck, J. E., Cockburn, M., Ling, C., Hershman, J. M., & Harari, A. (2022). Thyroid cancer and pesticide use in a Central California agricultural area: A case control study. The Journal of Clinical Endocrinology & Metabolism, 107(9), e3574–e3582. https://doi.org/10.1210/clinem/dgac413

Park, A. S., Ritz, B., Yu, F., Cockburn, M., & Heck, J. E. (2020). Prenatal pesticide exposure and childhood leukemia: A California statewide case control study. International Journal of

Hygiene and Environmental Health, 226, Article 113486. https://doi.org/10.1016/j.ijheh.2020.113486

Park, S. K., Kang, D., Beane Freeman, L. E., Gwak, J., Hoppin, J. A., Sandler, D. P., Knott, C., Lynch, C. F., Blair, A., & Alavanja, M. C. R. (2009). Cancer incidence among paraquat exposed pesticide applicators in the Agricultural Health Study. International Journal of Occupational and Environmental Health, 15(3), 274–281. https://doi.org/10.1179/oeh.2009.15.3.274

Paul, K. C., Cockburn, M., Gong, Y., Bronstein, J., & Ritz, B. (2024). Agricultural paraquat dichloride use and Parkinson's disease in California's Central Valley. International Journal of Epidemiology, 53(1), Article dyae004. https://doi.org/10.1093/ije/dyae004

Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., McInerney, P., Godfrey, C. M., & Khalil, H. (2020). Updated methodological guidance for the conduct of scoping reviews. JBI Evidence Synthesis, 18(10), 2119–2126. https://doi.org/10.11124/JBIES-20-00167

Pollock, D., Peters, M. D. J., Khalil, H., McInerney, P., Alexander, L., Tricco, A. C., Evans, C., de Moraes, É. B., Godfrey, C. M., Pieper, D., Saran, A., Stern, C., & Munn, Z. (2023). Recommendations for the extraction, analysis, and presentation of results in scoping reviews. JBI Evidence Synthesis, 21(3), 520–532. https://doi.org/10.11124/JBIES-22-00123

Roberts, T. R., Dyson, J. S., & Lane, M. C. G. (2002). Deactivation of the biological activity of paraquat in the soil environment: A review of long term environmental fate. Journal of Agricultural and Food Chemistry, 50(13), 3623–3631. https://doi.org/10.1021/jf011323x

Sartori, F., & Vidrio, E. (2018). Environmental fate and ecotoxicology of paraquat: A California perspective. Toxicological & Environmental Chemistry, 100(5–7), 479–517. https://doi.org/10.1080/02772248.2018.1460369

Shrestha, S., Parks, C. G., Umbach, D. M., Richards-Barber, M., Hofmann, J. N., Chen, H., Blair, A., Beane Freeman, L. E., & Sandler, D. P. (2020). Pesticide use and incident Parkinson's disease in a cohort of farmers and their spouses. Environmental Research, 191, Article 110186. https://doi.org/10.1016/j.envres.2020.110186

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., . . . Straus, S. E. (2018). PRISMA extension for scoping reviews, PRISMA ScR: Checklist and explanation. Annals of Internal Medicine, 169(7), 467–473. https://doi.org/10.7326/M18-0850

U.S. Environmental Protection Agency. (2019). Preliminary ecological risk assessment for the registration review of paraquat. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100XRRJ.TXT

U.S. Environmental Protection Agency. (2020). Paraquat dichloride: Proposed interim registration review decision, Case Number 0262. https://www.regulations.gov/document/EPA-HQ-OPP-2011-0855-0209

U.S. Environmental Protection Agency. (2021). Paraquat dichloride interim registration review decision, Case Number 0262. https://www.regulations.gov/document/EPA-HQ-OPP-2011-0855-0307

U.S. Environmental Protection Agency. (2025a, November 13). EPA updates review on potential paraquat volatilization and plans to request additional data from manufacturers.

https://www.epa.gov/pesticides/epa-updates-review-potential-paraquat-volatilization-and-plans-request-additional-data

U.S. Environmental Protection Agency. (2025b). Paraquat dichloride: One sip can kill. https://www.epa.gov/pesticide-worker-safety/paraquat-dichloride-one-sip-can-kill

U.S. Environmental Protection Agency. (2026a). Paraquat dichloride. Retrieved July 28, 2026, from https://www.epa.gov/ingredients-used-pesticide-products/paraquat-dichloride

U.S. Environmental Protection Agency. (2026b, June 30). EPA to host roundtable on paraquat this summer. https://www.epa.gov/newsreleases/epa-host-roundtable-paraquat-summer

Vermont General Assembly. (2026). Act No. 112: An act relating to prohibiting the use and sale of the herbicide paraquat. https://legislature.vermont.gov/Documents/2026/Docs/ACTS/ACT112/ACT112%20Act%20Summary.pdf