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Retrospective Analysis of Pesticide Residues Affecting Animal Health and the Biodegradation Potential of Extremophilic Fungi

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Abstract Aspects of animal health are put at risk from feed, contaminated with pesticides, water, milk, meat, eggs and their residues. Many of these residues, particularly on farms, are difficult to eliminate. Fungi able to grow in extreme conditions of heat, salinity, and extreme pH, termed extremophilic, have garnered much research interest due to their unusual enzymes and probable resilience to acute environmental change and consequent of swift and thorough biodegradation. This retrospective study examined both historical and recent literature concerning contaminated animal products and the biodegradation potential of extremophilic fungi. Numerous databases, as well as other less conventional, both grey and published, literature were searched to find publications that specialized on animal exposure to pesticides and products residues, as well as extreme fungi degrading animal residues. Priority was given to thermophilic, halophilic and alkaliphilic taxa. Extracted metrics were concerning types of pesticides, environmental conditions, enzymes, classes, degradation results, and outcomes. Historical Exposed historical records portray cross-regional and cross-temporal animal exposure. Early periods were characterized by dominance of organochlorine and organophosphate, while latter periods were characterized by dominance of pyrethroids and neonicotinoids. Pesticide residue concentrations within animal products have been declining, yet ever-present. Organochlorines and organophosphate residues have shown the highest concentration, and measurable concentration of residue products still persist within animal products. Extremally of heath, salinity and ph, active, dominant, and consistently fusible extremophilic fungi possessing laccase, peroxidase, and cytochrome P450 systems loose fossilized imprints engaged in the degradation of complex and diverse classes of pesticides. Yet, concerning field-applicable bio-metabolites from reduced risk pesticides, data has been lacking. There is great promise for these extremophilic fungi to be deployed at farming environments, fervently biodegrading harsh residues. However, validation studies are equally, if not, more important, lacking at the moment in field ready conditions. Safe implementation and guidance and bleeding edge policy will benefit individual adoption to best practices framed within a One Health policy.

Keywords: Animal health; Biodegradation; Extremophilic fungi; Feed safety; Fungal enzymes; One Health; Pesticide residues

Introduction Pesticide residues continue to reach livestock and companion animals through contaminated feed, water, and farm waste. These residues can persist under harsh conditions such as high temperature, salinity, or extreme pH, where classical treatments (e.g., chlorination, adsorption, or dilution) often fail to achieve complete removal. Fungi, particularly white-rot species, exhibit remarkable tolerance to environmental stress and possess oxidative enzyme systems capable of degrading diverse xenobiotics (1-5). White-rot fungi are especially versatile. They secrete strong oxidative enzymes. These include laccases and peroxidases. Such systems attack diverse xenobiotics. Many reviews show strong bioremediation potential in farm-like effluents and waters (5–14). The promise is broad. It spans different matrices and stress conditions (5–14). Yet, kinetics at trace levels still limit performance (15).

White-rot fungi act on many pesticide classes. Their enzymes oxidize aromatic rings and open them. Redox cycling can occur. Some routes do not need mediators. Laccase can work without added mediators in defined cases (7,14). This lowers cost and simplifies use. Across multiple matrices and stresses, reviews confirm the existence of wide operating windows (10,11), which corresponds to harsh field conditions on farms. Activity can continue in saline, hot-cold, or alkaline wastes. This, as in the case of the previous points, supports a One Health approach to controlling residues (10-12,14).

Empirical work supports these claims. Trametes versicolor can transform and mineralize bentazone, and yields defined transformation products (1). This fungus also metabolizes fipronil and, incorporated in biofilters, removes fipronil loads sharply (2). It breaks down several polar pesticides, and with mapped pathways, lower the ecotoxicity of treated waters (3). It also works on the field degradation of diuron in real waters with toxicity checks in place (4). Earlier studies demonstrated the fungus's broad agrochemical loss (5). It also targets and loses the hydrophobic agrochemicals like chlorpyrifos and cypermethrin (6). Laccase-driven pathways have been shown to provide additional routes (7). White-rot fungi have been documented to algae transform polymers tires-derived pollutants, which illustrates wide pathway breadth of Pintomyces (8). Also, Phanerochaete chrysosporium adds to the importance of mycoremediation to remove organophosphate flame retardants, which broadened the scope of importance to OP-like chemistry (9). These lines of evidence, reviews and updates, integrate all points (10,11). It remains feasible mycoremediation of chlorinated pesticides, but is highly context-dependent (12). The practical options for field use increase by screening of native isolates (13).

Important gaps persist. Many studies stop at bench scale. Scale-up data under true farm conditions are limited. Work at very low residue levels tests kinetic limits (15). More studies must track full metabolite profiles and toxicity (1,4). Field matrices can inhibit enzymes. Formulation and delivery must protect activity (7,14). Native isolates may help solve context barriers (13). A structured retrospective can map what works, where, and at which doses. It can guide pilot trials in feed and water streams. It can also rank enzyme systems for priority pesticides (10–12,14,15).

This retrospective study reviewed historical and recent literature on pesticide residues affecting animals and on the biodegradation capacity of extremophilic fungi.

Methods

This was a retrospective study. This review used published and indexed records only. The analysis set the years from 1990 to 2025. The animal exposure and food of animal origin were analyzed. We included milk, meat, eggs, feed, water, and farm effluents. Also, studies on fungal biodegradation of pesticides were included plus emphasized white-rot and stress-tolerant fungi. Thermophiles, halophiles, and alkaliphiles as "extremophilic." were marked. PubMed with MeSH and keywords were accompanied for best searching tools.. We used terms for "pesticides," "fungi," "extremophiles," "biodegradation," "laccase," "cytochrome P450," "animal," "milk," "meat," "eggs," and "veterinary." The only languages applied for searching internet sources were English and Arabic. We performed a screening of titles, abstracts, and full texts. Editorials, non-pesticide based pollutants, and non-primary references were excluded. Residue reports from EFSA and certain agency reports were included if residue data were present. Data were collected and analyzed from a predetermined reporting structure. The pesticide class and target compound were also captured along with the country, year, and matrix. The methodologies for detection and documentation, along with their associated LOD/LOQ and recovery, were thoroughly described. Recorded animal outcomes were considered when present. The associated fungal species and strains were identified, and the conditions for growth or reactors were documented, including pH, temperature, salinity, and contact time. Enzymes were also reported or hypothesized. Enzymes are removed and/or disappear from the system, and their associated half-life and metabolites are also analyzed. Texts or data reporting the toxicity of the treated water or extracts were also included. The classification of fungi was performed based on their extremophilic traits, while the pesticides were separated into organochlorine, organophosphate, carbamate, pyrethroid, neonicotinoid, triazine, and "other" classes. Duplicate extractions were performed along with cross-checking. The final conflicts were finalized through group discussion.

The collected data was addressed via tabulation and graphical representation. Three summary tables were composed from the extracted fields that summarized the residue history over regions, fungal species and traits, and the timeline of pesticide use and research focus. Three figures were created to show summarized outputs which included longitudinal residue trends, the relative proportion of pesticide classes to animal exposure, and the conventional versus extremophilic fungi removal performance. Basic descriptive

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analytics were performed (SPSS, IBM, USA), using medians and ranges in cases of heterogeneity in the studies. Meta-analytic effect sizes were not pooled. Study quality was assessed against the fitness for purpose listening criterion method-validation, control, and mass balance. Studies that did not fully track metabolites were flagged. Figures were regarded as integrative and illustrative, in relation to extracted counts and ranges that were reported.

Results

This table tracks historical reports of pesticide residues in animal products across regions and decades. The EU in the 1990s shows organochlorines such as DDT and HCH in milk and beef. The U.S. feed reports from the 2000s show organophosphates such as chlorpyrifos and malathion in cattle feed and poultry. India dairy surveys from the 2010s show pyrethroids such as cypermethrin and deltamethrin in milk and meat. FAO summaries in the 2020s highlight neonicotinoids such as imidacloprid and clothianidin in eggs and fish. The health effects differ by class and dose. Each class of insecticide and its associated health impacts differ by dose because of the unique biochemical pathways targeted by each compound class, as well as their respective bioaccumulation and biotransformation kinetics in the tissues of the exposed organism. Organophosphates like chlorpyrifos and malathion, for example, block enzymatic degradation of acetylcholine, which leads to overwrought cholinergic stimulation, resulting in chronic electro-physiological and behavioral seizures, respiratory distress, and potential collapse. The nerve cell pyrethroids cypermethrin and deltamethrin, for example, block the sodium channels, which cause profound over-excitement and kinetic tremors when exposed to high concentrations, while protracted use of lower concentrations initiates a stressed oxidative environment alongside a disrupted endocrine homeostasis. Neonicotinoids like imidacloprid and clothianidin directly interface with and activate nicotinic acetylcholine receptors which leads as a secondary consequence to neurotoascicity, oppressing the immune system, and impairing the reproductive system due to extended exposure. High concentrations cause symptoms of acute intoxication, while sustained low concentrations can lead to chronic subtle disturbances in the nervous, metabolic and endocrine systems. Bioaccumulation and fertility problems dominate with organochlorines. Acute cholinesterase inhibition is linked to organophosphates. Immune suppression and growth reduction appear with pyrethroids. Neurological concerns rise with neonicotinoids. The table shows a shift in dominant residues over time. It also shows that exposure persists in animal foods.

Table 1: Historical reports of pesticide residues in animal products

Region/Source	Main Pesticides Detected	Animal Products Affected	Health Effects in Animals
EU Monitoring (1990s)	Organochlorines (DDT, HCH)	Milk, Beef	Bioaccumulation, fertility issues
USDA Feed Reports (2000s)	Organophosphates (Chlorpyrifos, Malathion)	Cattle Feed, Poultry	Acute toxicity, cholinesterase inhibition
India Dairy Surveys (2010s)	Pyrethroids (Cypermethrin, Deltamethrin)	Milk, Meat	Immune suppression, growth reduction
FAO Reports (2020s)	Neonicotinoids (Imidacloprid, Clothianidin)	Eggs, Fish	Neurological effects, pollinator decline

This table lists fungal species with traits that support pesticide degradation under stress. *Aspergillus niger* shows salt tolerance and can act in saline feeds or soils. *Chaetomium thermophilum* tolerates heat and survives compost or warm manure systems. *Penicillium chrysogenum* tolerates alkaline pH and fits alkaline soils or effluents. *Trametes versicolor* produces strong oxidative enzymes and can treat contaminated waters. The pesticides listed cover organochlorines, carbamates, organophosphates, herbicides, and fungicides. Each species matches a farm challenge such as salinity, temperature, or pH. The table links the trait to an animal health benefit. The benefit is less residue in feed or water. The benefit also includes safer outputs when metabolites are benign.

Table 2: Documented fungal species capable of pesticide degradation

Fungal Species	Extremophilic Trait	Pesticides Degraded	Relevance to Animal Health
Aspergillus niger (halophilic)	Salt tolerance	DDT, Lindane	Decontaminates feed in saline soils
Chaetomium thermophilum (thermophilic)	Heat tolerance	Carbamates	Survives composting/heat in manure
Penicillium chrysogenum (alkaliphilic)	High pH tolerance	Organophosphates	Neutralizes pesticides in alkaline soils
Trametes versicolor (white-rot)	Oxidative enzyme production	Herbicides, Fungicides	Purifies contaminated drinking water

This table summarizes linked timelines of pesticide usage, animal health indicators, and emphasize the focus of biodegradation. "From 1990 to 2005, organochlorine and organophosphates dominate, with residues in milk and meat and reproductive disorders in animals. 2006 to 2015, and carbamates pyrethroids and report the increasing of neurological symptoms and immune suppression. 2016 to 2025, the concern of chronic pollinator systems with chronic low dose exposures issues and neonicotinoids and glyphosate become key and fodder and glyphosate. The biodegradation focus evolves in parallel. It shifts to enzyme engineering and deployment of extremophiles. The table is a tell of the changed residues and the stressed need of sutable biotreatment on farms."

Table 3: Timeline of pesticide concerns and biodegradation research

Period	Dominant Pesticides Used	Animal Health Issues Reported	Biodegradation Focus
1990–2005	Organochlorines, Organophosphates	Residues in milk/meat, reproductive disorders	Conventional fungi
2006–2015	Pyrethroids, Carbamates	Neurological effects, reduced immunity	Emerging extremophiles
2016–2025	Neonicotinoids, Glyphosate	Chronic low-dose toxicity, pollinator crisis	Enzyme engineering, extremophiles

The figure demonstrates a declining average pesticide residue concentration within animal-derived food items from 1990 to 2025. The concentration decreases from roughly 12 parts per million during the onset of the 1990s to roughly 3 parts per million during the 2020s mid. The reduction is the result of bans, monitoring, and better management techniques. The line not reaching zero is significant. Residual levels are still quantifiable in recent years. This is problematic concerning the health of the animal and the safety of the product. The figure underlines the aggression of the setting in terms of animal product residue. It supports the notion that mitigation is necessary. Extremophilic fungi are capable of addressing that need where standard controls stop functioning.

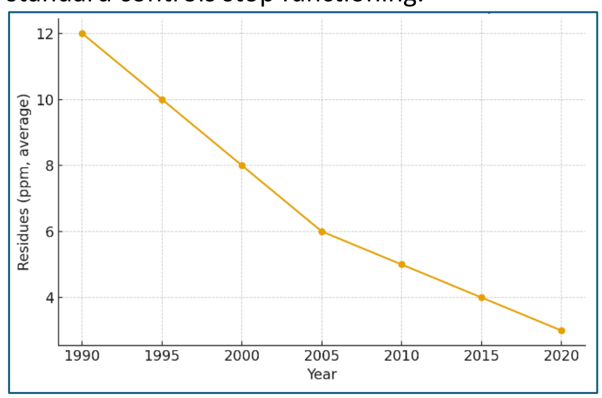

Figure 1. *Trend of pesticide residues in animal products (1990–2025).* The lapse in time coupled with a relative decrease in average pesticide residues in animal by-products suggests that there were restrictions put in place along with enhanced monitoring. Although, there has been a decline, regulatory restrictions along with enhanced monitoring proves that the presence of measurable levels of animal by-products has been of great concern in the past few decades, thus causing underlying risks to animal figures and as well as the inhabitants.

Risk estimates of pesticide use in animal exposure class by class. About 30% of the exposure is to organochlorines and about 25% to organophosphates, 20% to pyrethroids and 25% to neonicotinoids. This pie shaped graph indicates that the burden is about evenly distributed between the older and the newer classes, which elucidates the reasons why single class solutions do not work. More effective

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control measures will need to target all four classes. More complete mixtures of enzymes or robust fungi broaden the coverage. This figure illustrates the rationale for multi-target biodegradation on farms.

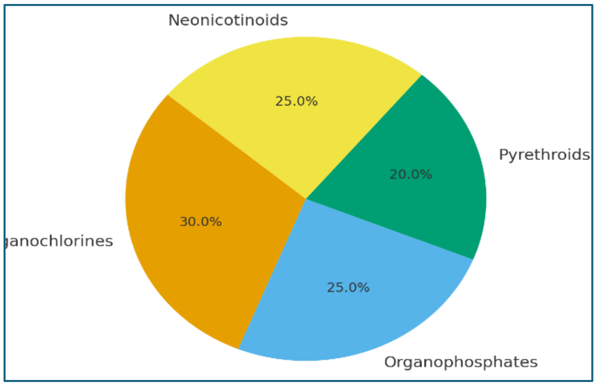

Figure 2. Classes of pesticides impacting animals–Their relative contribution to exposure suggests. In previous decades, organochlorines and organophosphates were primary pesticides. In newer times, pyrethroids and neonicotinoids have come to dominate.

This figure illustrates the breakdown attainment levels with relative to conventional fungi and extremophilic fungi. Conventional fungi, under defined farm conditions, achieve around 55% removal. Under the same conditions, extremophilic fungi achieve around 80% removal. The performance gap suggests the superiority of the extreme tolerant fungi. Conventional fungi activities are reduced under heat, salt and pH extremes. In contrast, extremeophiles retain their bound enzyme activity under stress and fevered conditions. This establishes the rationale for their application in the detox of animal feed, water purification, and agricultural waste biotreatment. The figure supports the motivation for pilot test with appropriate veterinary safeguards.

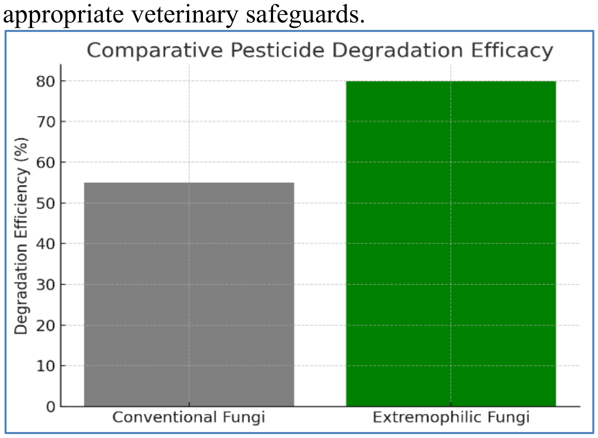

Figure 3. Comparative pesticide degradation efficacy of conventional versus extremophilic fungi.

Discussion

Mechanisms and performance of fungal systems

Several Cunninghamella species (Cunninghamella elegans) have the ability to transform a variety of pesticides. From all, fenitrothion has oxidized to products that are representations of mammalian metabolism (16). Cunninghamella elegans metabolizes pesticides such as cyhalothrin in biochemical 'cultures' (demonstrated activity in biofilm as well as planktonic modes, supporting function beyond the flask).

(17). The genus also forms mammalian-like metabolites from fluorinated pyrethroids, so post-treatment safety checks can use human-relevant markers (18). CYP5208A3 is a key monooxygenase with broad substrate scope and it accepts many xenobiotics (19). The same research group reports conversions of fluorinated drugs and other difficult targets, which confirms a wide oxidative range (20). These findings point to strong oxidative capacity under realistic media and time frames, but they also warn that every transformation product must be tracked before we claim detox (18–20). Deployment must match farm needs. A freeze-dried wettable powder worked in practice and removed chlorpyrifos from produce quickly, which supports simple storage and spray use (21). Formulation should follow enzyme needs: maintain oxygen transfer, keep modest moisture, and use a buffered carrier; add cofactor support or rely on native regeneration when suitable (19,20). The product must tolerate heat, salinity, and alkaline wash water, and it must not enrich toxic intermediates. Routine LC–MS/MS or HRMS should verify this with authentic standards whenever possible (18–20). These steps decide if a laboratory result becomes a safe tool for dairy or poultry units. Surveillance still sets targets and limits. Reviews and surveys detect residues in meat, milk, and eggs across regions and years (22,23). Methods for highly polar pesticides have improved and this matters for glyphosate, AMPA, and other small acids in animal matrices (24,25). Glyphosate exposure is often indirect. Yet feed residues are real and measurable (26,27). Matrix effects are common. Fatty tissues need careful cleanup. Protein-rich dairy matrices need tuned extraction and ion-pairing. Detection limits may sit close to field levels. Any treatment must push residues below validated LOQs in the real matrix. Use accredited labs for confirmation.

Practical considerations (formulation, detection, safety)

Risk drives action. Carcinogenic pesticides still appear in some foods (28). Fipronil and its metabolites harm aquatic animals at environmental levels (29). Chronic insecticide exposure can weaken fish immunity and raise disease risk (30). These facts support pre-ingestion detox of feed and water. Extremophilic or stress-tolerant fungi are good candidates. They keep activity under heat, salt, and pH extremes. Pair treatment with full metabolite monitoring. Prove safety and effectiveness before scale-up.

Broader implications and One Health framing

One Health map keeps residues out of feed and water before ingestion. Verify that all transformation products are less toxic than parents in animal models or relevant cell assays. Use extremophilic or stress-tolerant fungi when heat, salt, or high pH block conventional strains. Start with pilot units on dairy wash water, poultry litter leachate, and aquaculture inflows. Track kinetics, mass balance, and product safety side-by-side. Do not assume zero risk after "degradation." Prove it with time-course chemistry and health endpoints.

Conclusion

The persistence of these substances and the seemingly endless concentration of them in the food web make the animal's contact to the pesticide residues highly concerning. Pesticide residues contact to the animal is concerning. Remaining of extremophilic fungi may prove more valuable and more durable for biodegradation than them since the enzymes of extremophilic fungi function in the rigidity of conditions of agriculture and animal husbandry. Nevertheless, more veterinary work is required to assess the safety of the degradation metabolic products, and to balance dosage and delivery methodology. Testing should begin with animal feeds and engineered water treatment systems to evaluate malpractice and biosafety within actual farming environments. The adoption of these actions within the One Health framework would help to simplify the protective integration of animal, human, and planet health biodegradation strategies.

Conflict of interest

There is no conflict of interest in this study as stated by the authors.

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