

Effect Of Different Concentrations Of A Common Pharmaceutical Compound On Seed Germination And Early Seedling Growth: A Review

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Abstract—Pharmaceutical residues are increasingly recognized as emerging environmental contaminants due to their continuous release from domestic wastewater, hospitals, pharmaceutical industries, improper medicine disposal, and wastewater reuse. Because pharmaceutical compounds are biologically active, their occurrence in aquatic and terrestrial environments may influence non-target organisms, including plants. Paracetamol (acetaminophen), one of the most widely used analgesic and antipyretic drugs, has been detected in wastewater and surface-water systems and has consequently attracted attention in environmental toxicity studies.

This short review summarizes the environmental pathways of pharmaceutical contamination and examines the reported effects of paracetamol on seed germination and early seedling development. It places particular emphasis on the influence of concentration, exposure duration, plant species, and the developmental stage examined. Available evidence indicates that pharmaceutical exposure may not affect all plant responses equally. In wheat (*Triticum aestivum*), increasing paracetamol concentrations were associated with significant reductions in root and shoot elongation, whereas germination frequency was not significantly affected under the tested conditions. Root growth appeared to be particularly sensitive, and biochemical responses involving chlorophyll accumulation, soluble proteins, and antioxidant enzyme activity were also reported. Studies involving *Lactuca sativa* and other plant systems further indicate that responses may vary between individual pharmaceutical compounds and mixtures.

These observations highlight the importance of evaluating both germination and post-germination growth when assessing pharmaceutical phytotoxicity. Comparative studies involving multiple concentrations and representative monocotyledonous and dicotyledonous species are warranted to understand better concentration-dependent responses and the

potential ecological significance of pharmaceutical residues in the environment.

Index Terms—Paracetamol; Acetaminophen; Pharmaceutical residues; Emerging contaminants; Seed germination; Seedling growth; Phytotoxicity; Root elongation; Shoot elongation; Environmental contamination

I. INTRODUCTION

Pharmaceutical residues are increasingly recognized as emerging environmental contaminants because their continuous use and disposal introduce biologically active compounds into wastewater, surface water, and terrestrial environments. Major pathways include domestic wastewater, hospital effluents, pharmaceutical industries, improper medicine disposal, and reuse of treated wastewater for irrigation. Consequently, pharmaceutical residues may reach agricultural soils and plants through wastewater, biosolids and other environmental routes (Carvalho et al., 2014; Wei et al., 2023).

Unlike many conventional pollutants, pharmaceuticals are specifically designed to interact with biological systems. Their presence in the environment can therefore produce responses in non-target organisms, including plants. Studies have reported pharmaceutical uptake by plants and associated changes in growth, physiological processes and biochemical responses, although the magnitude of these effects depends on the pharmaceutical, concentration, exposure duration and plant species (Carvalho et al., 2014; Wei et al., 2023). Paracetamol (acetaminophen) is a widely used analgesic and antipyretic and has been investigated as a representative pharmaceutical contaminant. An et al.

(2009) reported that increasing paracetamol concentrations significantly inhibited root and shoot elongation in wheat (*Triticum aestivum*), with roots showing greater sensitivity, whereas seed germination was not significantly affected under the experimental conditions. Biochemical changes involving chlorophyll, soluble proteins, and antioxidant enzymes were also observed following exposure.

Importantly, pharmaceutical exposure may therefore affect post-germination development even when germination itself remains unaffected. Supporting this observation, Pino et al. (2016) reported inhibitory effects of several pharmaceuticals on radicle and hypocotyl elongation of *Lactuca sativa*, while germination remained unaffected at the concentrations tested. Similarly, exposure to paracetamol, ibuprofen

and amoxicillin, individually and in mixtures, has been investigated in *L. sativa*, with effects observed on early plant growth.

Thus, germination percentage alone may not adequately represent pharmaceutical-induced phytotoxicity. Root and shoot elongation, together with selected physiological or biochemical parameters, can provide additional information about early plant responses. The present review therefore focuses on the concentration-dependent effects of paracetamol on seed germination and early seedling growth, while considering the influence of exposure conditions and plant species. Such an approach is particularly relevant for identifying subtle effects that may occur after germination and for defining priorities for comparative phytotoxicity studies.

Table 1. Selected studies on pharmaceutical effects on seed germination and early plant growth

Study	Compound(s)	Plant	Key observation
An et al. (2009)	Paracetamol	<i>Triticum aestivum</i>	Root and shoot growth decreased with increasing concentration; germination was unaffected.
Pino et al. (2016)	15 pharmaceuticals	<i>Lactuca sativa</i>	Several pharmaceuticals inhibited radicle/hypocotyl growth, while germination remained unaffected.
Carvalho et al. (2014)	Pharmaceuticals	Crop plants	Reviewed plant uptake, phytotoxicity, and environmental exposure pathways.
Nunes et al. (2019)	Paracetamol, ibuprofen, amoxicillin	<i>Lactuca sativa</i>	Individual and combined pharmaceuticals affected early plant growth.
Wei et al. (2023)	Pharmaceuticals/PPCPs	Multiple plant systems	Uptake, accumulation, and physiological responses vary with compound and plant characteristics.

The literature summarized above supports the central observation that early seedling growth can be a more responsive endpoint than germination alone.

II. PHARMACEUTICAL RESIDUES IN THE ENVIRONMENT AND PLANT EXPOSURE

Pharmaceutical residues enter the environment through several interconnected pathways, making their occurrence a continuous rather than isolated contamination problem. Following human or veterinary use, pharmaceutical compounds and their metabolites may reach domestic sewage through excretion. Hospital wastewater, pharmaceutical manufacturing effluents, improper disposal of unused medicines, and wastewater reuse represent additional sources. Conventional wastewater treatment may not eliminate all pharmaceutical compounds, allowing residues to remain in treated effluents or sludge and

subsequently enter receiving water bodies and terrestrial environments (Carvalho et al., 2014; Rivera-Utrilla et al., 2013). The source material similarly identifies domestic wastewater, hospitals, pharmaceutical industries, improper disposal, and wastewater reuse as major pathways of pharmaceutical contamination.

Aquatic systems are particularly important in the environmental movement of pharmaceutical residues because wastewater discharges can introduce these compounds into rivers, lakes, and groundwater. Pharmaceutical residues, including paracetamol, have been reported in Indian river systems such as the Yamuna and Ganges, showing that pharmaceutical contamination also affects water resources that interact with human and agricultural activities. Once present in water, residues may reach plants directly through aquatic exposure or indirectly through the use of contaminated water for irrigation.

Agricultural soils represent another important environmental compartment. Applying treated wastewater, biosolids, manure, and other reclaimed materials can introduce pharmaceutical residues into soil, where their persistence and mobility depend on physicochemical properties, soil characteristics, and degradation processes (Carvalho et al., 2014; Wei et al., 2023). Sorption and desorption, biodegradation, and abiotic transformation influence the fraction of a pharmaceutical available for plant uptake. Consequently, concentrations in soil or water may change over time rather than remaining constant (Wei et al., 2023).

Depending on the environmental setting, plants may encounter pharmaceutical residues through roots, contaminated water, or foliar exposure. Root uptake is particularly relevant for crops irrigated with reclaimed wastewater or cultivated in contaminated soils. After uptake, pharmaceuticals may remain in roots or translocate to aerial tissues. Factors such as molecular size, hydrophobicity, ionization behavior, pH, transpiration, and the physicochemical characteristics of both the compound and plant tissue influence uptake and movement within plants (Hu et al., 2015; Wei et al., 2023).

Importantly, environmental exposure does not necessarily translate directly into visible toxicity. Plant responses depend on compound concentration, exposure duration, plant species, and environmental conditions. Nevertheless, continuous exposure may affect plant growth and physiological processes, making early plant development a useful system for evaluating potential effects. The source material emphasizes that pharmaceutical exposure may influence root and shoot development even when germination itself remains unaffected. Thus, understanding how pharmaceutical residues move from environmental sources to plants provides an essential basis for evaluating their concentration-dependent effects on seed germination and early seedling growth.

III. PARACETAMOL AS AN EMERGING ENVIRONMENTAL CONTAMINANT

Paracetamol (acetaminophen; N-acetyl-p-aminophenol) is one of the most widely used analgesic and antipyretic pharmaceuticals and is available in numerous prescription and non-prescription

formulations. Its widespread use and subsequent excretion or disposal have contributed to its presence in wastewater and receiving waters. Paracetamol is therefore increasingly considered an environmentally relevant pharmaceutical micropollutant rather than solely a therapeutic compound (Hien et al., 2019). Reviews of pharmaceutical contamination have identified acetaminophen as a frequently detected pharmaceutical compound in aquatic environments, including Indian water systems (Subedi et al., 2017; Ranjan et al., 2022).

Paracetamol occurs primarily in the environment through domestic wastewater, healthcare activities, and pharmaceutical-related discharges. After entering wastewater, dilution, degradation, treatment efficiency, and transformation influence its environmental concentration. Hien et al. (2019) reported that paracetamol can occur in wastewater and in surface-water and groundwater compartments and may transform into several intermediate products. Importantly, environmental transformation does not necessarily imply complete elimination, as some transformation products may possess biological activity of their own.

The occurrence of paracetamol in environmental waters provides a potential route for non-target plant exposure, particularly where contaminated water is used for irrigation or enters agricultural and aquatic ecosystems. Plants may interact with pharmaceutical residues through their roots or other exposed tissues, and the resulting response can depend on exposure concentration and duration, as well as species-specific characteristics. Thus, the environmental significance of paracetamol extends beyond its measured concentration in water to its potential biological effects following repeated or prolonged exposure.

Evidence from plant toxicity studies directly supports this concern. An et al. (2009) investigated the effects of paracetamol on wheat (*Triticum aestivum*) and found that increasing concentrations significantly reduced both root and shoot elongation, with roots being particularly sensitive. In contrast, seed germination was not significantly affected under the concentrations tested. The study also reported changes in chlorophyll accumulation, soluble protein synthesis, and antioxidant enzyme activities following exposure. These findings matter because they show that paracetamol's environmental effects may become apparent after successful germination, rather than

necessarily preventing germination itself. Consequently, root and shoot development can provide valuable endpoints for detecting pharmaceutical-induced stress that might be overlooked when considering germination percentage alone. The source material similarly emphasizes the distinction between germination and subsequent seedling development.

Overall, paracetamol represents a useful model pharmaceutical for examining concentration-dependent plant responses. Its widespread occurrence, continuous environmental input, and demonstrated effects on early plant development provide a rationale for evaluating its influence across different concentrations and plant species.

IV. EFFECTS OF PHARMACEUTICAL EXPOSURE ON SEED GERMINATION AND EARLY SEEDLING GROWTH

Seed germination and early seedling development are sensitive stages of the plant life cycle and are widely used to evaluate the biological effects of environmental contaminants. During these stages, developing tissues undergo rapid cell division, elongation, and metabolic activation, making changes in germination, root growth, and shoot development useful indicators of environmental stress. Germination tests are also relatively simple and rapid compared with longer-term plant growth experiments, which makes them valuable for preliminary ecotoxicological assessment (Kaur et al., 2017).

Pharmaceutical exposure can influence plants at both the germination and post-germination stages, although the magnitude and direction of the response vary considerably among compounds and plant species. Reported responses include delayed or reduced germination, inhibited root and shoot elongation, altered seedling biomass, and changes in physiological and biochemical processes. A recent review of pharmaceutical-plant interactions further indicates that pharmaceuticals can affect root activity, oxidative status, and other physiological pathways, with responses depending strongly on compound concentration and plant characteristics (Wei et al., 2023).

A key observation in the literature is that germination percentage and seedling growth do not necessarily respond in the same way. An et al. (2009) investigated

paracetamol toxicity in wheat (*Triticum aestivum*) using seed germination, root length, and shoot height as major developmental endpoints. Increasing paracetamol concentrations significantly inhibited both root and shoot elongation, while the difference in germination percentage between treated and control seeds was not statistically significant. Roots were identified as the most sensitive plant site. This finding indicates that successful germination does not necessarily imply the absence of pharmaceutical-induced stress.

Wheat responses also extended beyond visible growth parameters. An et al. (2009) reported that prolonged exposure to relatively low paracetamol concentrations affected chlorophyll accumulation and soluble protein synthesis. Changes in antioxidant enzymes were also observed: peroxidase and superoxide dismutase activities increased in wheat leaves during shorter exposure, whereas prolonged exposure was associated with reduced peroxidase activity in roots. These findings suggest that pharmaceutical stress may involve physiological and biochemical responses before severe impairment of overall plant establishment becomes evident.

Evidence from other pharmaceuticals supports evaluating root and shoot development alongside germination. Pino et al. (2016) examined 15 commonly used pharmaceuticals using *Lactuca sativa* and found that 12 compounds inhibited radicle and/or hypocotyl elongation. However, even at the highest concentrations tested, seed germination was not affected. The study therefore provides further evidence that post-germination growth can be a more responsive endpoint than germination percentage for some pharmaceutical contaminants.

Similar observations have been reported for paracetamol in combination with other pharmaceuticals. Nunes et al. (2019) evaluated paracetamol, ibuprofen and amoxicillin individually and in binary and ternary mixtures using *L. sativa*. The study assessed germination, root elongation, shoot and leaf length after five days of exposure and reported indications of acute toxicity during early plant growth. These findings matter because environmental exposure generally involves mixtures rather than a single pharmaceutical compound.

The effects of pharmaceutical exposure are also concentration- and exposure-dependent. Higher

concentrations may produce progressively stronger inhibition of root or shoot development, while lower concentrations may show limited effects during short-term exposure. However, prolonged exposure can reveal responses that are not immediately apparent. In the wheat–paracetamol study, for example, low concentrations affected growth after chronic exposure, showing that concentration should not be considered independently of exposure duration (An et al., 2009). Overall, the available evidence suggests that pharmaceutical contamination can influence early plant development through multiple, interconnected responses. Germination, root elongation, shoot

elongation and physiological indicators should therefore be considered complementary rather than interchangeable endpoints. For paracetamol, available evidence indicates that root and shoot growth may be affected even when germination remains relatively stable. This distinction is particularly relevant when assessing concentration-dependent phytotoxicity and supports using multiple early-developmental endpoints in future comparative studies. The source material likewise emphasizes that pharmaceutical exposure may become more evident during seedling development than during the initial germination stage.

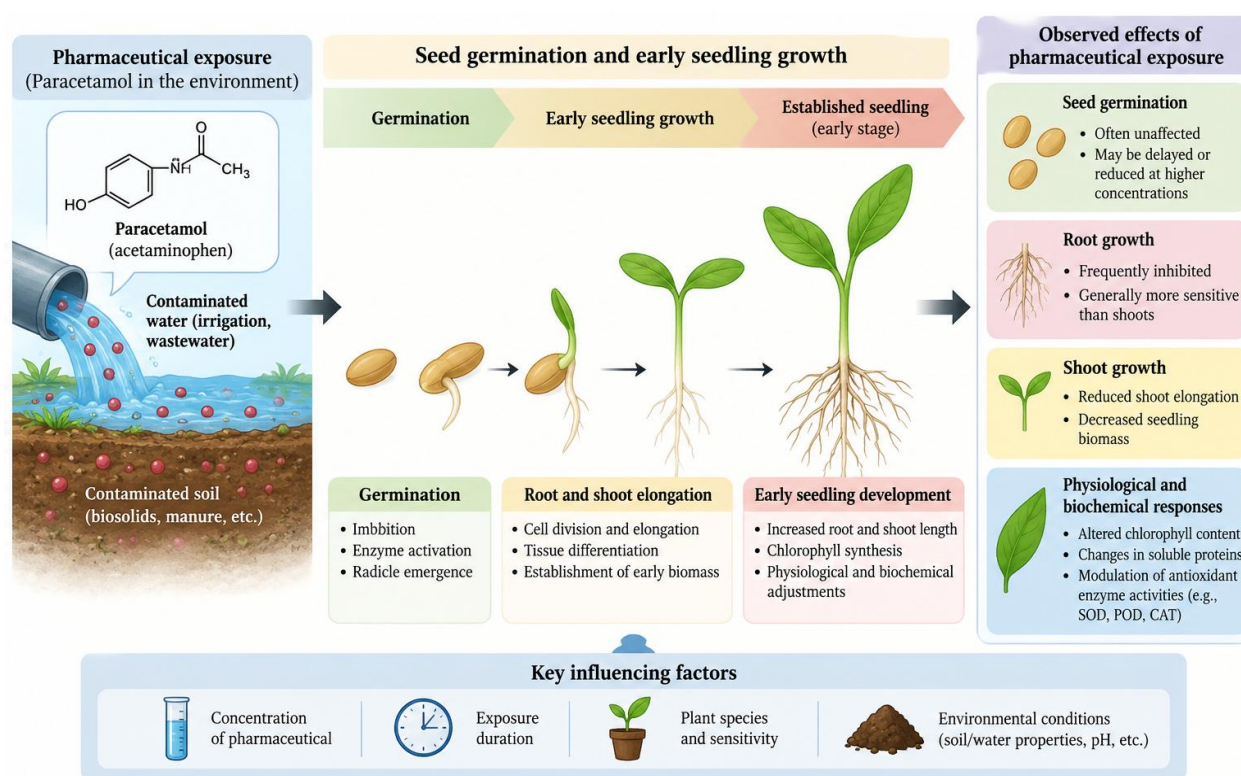


Figure 1. Effects of Pharmaceutical Exposure on Seed Germination and Early Seedling Growth

V. CONCENTRATION-DEPENDENT RESPONSES TO PARACETAMOL

The concentration of a pharmaceutical compound is an important determinant of its potential effects on plants. However, the relationship between concentration and phytotoxicity should be considered alongside exposure duration, plant species, and the endpoint being measured. For paracetamol, available evidence indicates that seed germination may remain relatively stable across a tested concentration range, whereas

root and shoot development can show a clearer concentration-dependent response.

The study by An et al. (2009) provides particularly relevant evidence for wheat (*Triticum aestivum*). Increasing paracetamol concentrations significantly reduced both root and shoot elongation, with a positive relationship between concentration and inhibition of these growth parameters. Root growth was more sensitive than shoot growth, and the reported EC₅₀ for inhibition of root elongation was 668.8 mg/L. In contrast, germination frequency did not differ

significantly from the control across the experimental concentrations. This contrast demonstrates that concentration-dependent toxicity may become evident during seedling development even when the initial germination process remains comparatively unaffected. Short-term and prolonged exposure can produce different responses. In the wheat study, relatively low paracetamol concentrations of 1.4–22.4 mg/L affected chlorophyll accumulation and soluble protein synthesis after 21 days of exposure. Changes in antioxidant enzyme activities were also observed, with peroxidase and superoxide dismutase activities in leaves increasing with concentration after 7 days, while peroxidase activity in roots decreased following 14 days of exposure. These findings indicate that concentration alone does not fully describe the biological response; a comparatively low concentration may produce measurable effects when exposure is sufficiently prolonged.

Evidence from other plant systems also demonstrates concentration-related responses. In *Lactuca sativa*, researchers assessed exposure to paracetamol, ibuprofen, and amoxicillin individually and in mixtures, using germination, root elongation, shoot length, and leaf length as endpoints. The study reported acute effects on early plant growth following

individual pharmaceutical exposure, while responses to mixtures differed from those observed for individual compounds (Rede et al., 2019). Furthermore, a study using *Lens culinaris* and *Pisum sativum* examined paracetamol concentrations ranging from 1 to 500 mg/L and reported inhibition of root growth, along with cytological abnormalities, across the tested treatments (2023 study). Recent work also suggests that the response can become apparent at physiological rather than purely morphological endpoints. In *Lactuca sativa*, plants exposed to 0, 5, 50, 500 μ M and 5 mM paracetamol for 14 days showed concentration- and exposure-regime-dependent changes in photosynthesis, chlorophyll and fluorescence parameters, with chronic exposure producing greater sensitivity than acute exposure (Hana et al., 2020).

Taken together, the available evidence indicates that paracetamol responses are endpoint-, concentration- and exposure-dependent. Germination may be comparatively insensitive within some concentration ranges, whereas root elongation, shoot growth and physiological or biochemical parameters may respond more clearly. Therefore, concentration-response experiments should ideally include multiple exposure levels and more than one biological endpoint rather than relying solely on germination percentage.

Table 2. Concentration-dependent responses reported following paracetamol exposure

Study	Plant system	Paracetamol exposure	Major response
An et al. (2009)	<i>T. aestivum</i>	Increasing concentrations; 1.4–22.4 mg/L in chronic exposure	Root and shoot elongation decreased with concentration; germination unaffected.
An et al. (2009)	<i>T. aestivum</i>	EC ₅₀ = 668.8 mg/L for root elongation	Root growth identified as the more sensitive endpoint.
Rede et al. (2019)	<i>L. sativa</i>	Individual/mixture pharmaceutical exposures	Early growth responses occurred; mixture responses differed from individual compounds.
2023 study	<i>L. culinaris</i> , <i>P. sativum</i>	1–500 mg/L	Root growth inhibition and cytological abnormalities were reported.
Hana et al. (2020)	<i>L. sativa</i>	0–5 mM	Photosynthesis, chlorophyll, and fluorescence responses varied with exposure and concentration.

Note: Concentrations and responses in the table are study-specific and should not be interpreted as a universal environmental dose-response relationship.

VI. SPECIES-SPECIFIC RESPONSES: MONOCOTS VERSUS DICOTS

Plant species can differ considerably in their response to pharmaceutical exposure because of differences in

seed structure, root architecture, growth rate, metabolism, uptake capacity, and physiological sensitivity. Consequently, observations obtained from a single plant species should not automatically be generalized to an entire botanical group. The source material emphasizes that differences in root structure, seed composition, growth characteristics, and physiological responses may influence responses to pharmaceutical contaminants.

Among monocotyledonous plants, wheat (*Triticum aestivum*) provides one of the better-documented examples for paracetamol exposure. An et al. (2009) reported that increasing paracetamol concentrations significantly reduced root and shoot elongation in wheat, with roots representing the more sensitive site. However, germination frequency was not significantly affected under the tested conditions. These findings demonstrate that a monocotyledonous crop can exhibit measurable post-germination responses even when the initial germination process remains relatively unaffected.

Comparative evidence involving both monocots and dicots suggests that sensitivity may differ even when plants are exposed to the same pharmaceutical. Zezülka et al. (2019), for example, examined paracetamol and diclofenac in onion, lettuce, pea and tomato seedlings, followed by investigations in pea and maize. Seed germination and primary root length of the tested species were not affected at the initial exposure stage, whereas longer exposure produced substantial physiological and biochemical responses. Notably, maize, a monocot, showed greater sensitivity in several oxidative-stress and photosynthetic parameters than pea under the experimental conditions.

Dicotyledonous species have also demonstrated variable responses to pharmaceutical exposure. In *Lactuca sativa*, exposure to paracetamol, ibuprofen and amoxicillin produced measurable responses in early growth, although responses differed between individual pharmaceuticals and their mixtures (Rede et al., 2019). Similarly, studies using *Lens culinaris* and *Pisum sativum* have reported reductions in root growth following paracetamol exposure, highlighting the usefulness of root elongation as a sensitive endpoint. These findings indicate that monocot–dicot comparisons are useful but should be interpreted cautiously. Current evidence does not establish that either monocotyledonous or dicotyledonous plants are universally more sensitive to paracetamol. Instead, responses appear to depend on the interaction between pharmaceutical concentration, exposure duration, species-specific characteristics, and the endpoint selected. Therefore, future studies should include multiple representative monocot and dicot species and evaluate both germination and post-germination parameters. Such comparative approaches would help determine whether observed differences reflect broad taxonomic patterns or simply species-specific responses.

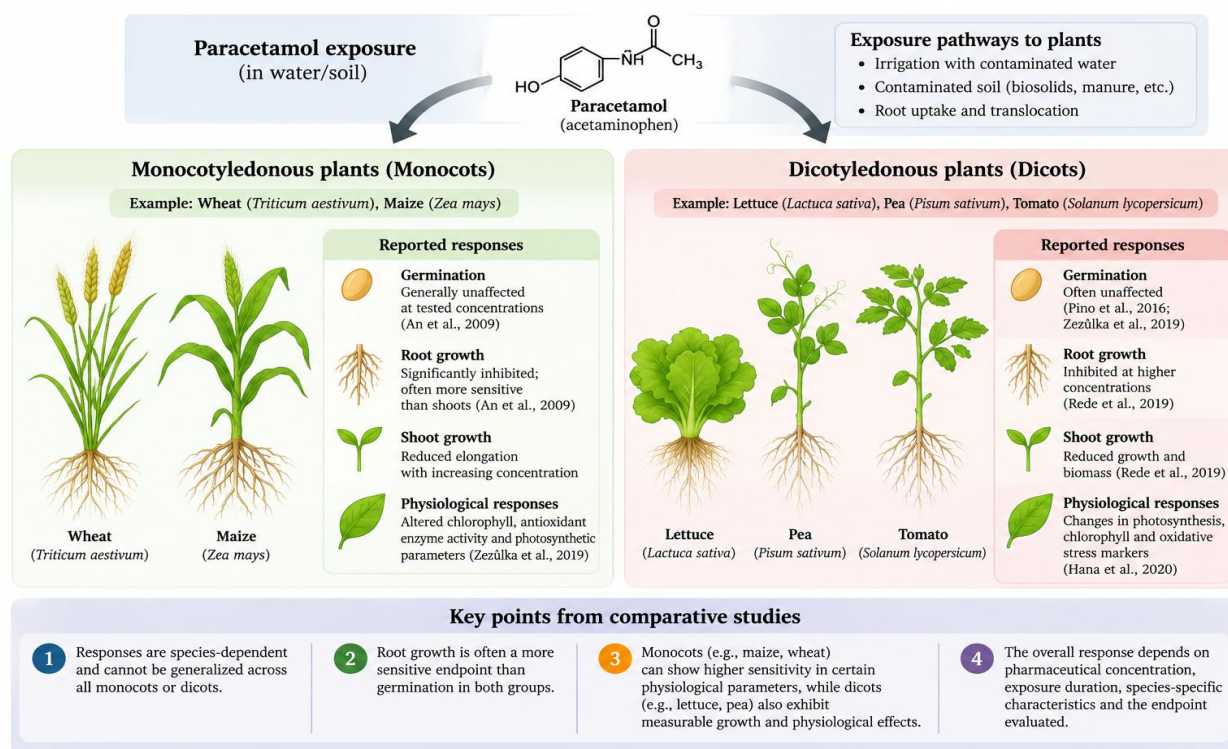


Figure 2. Comparative Responses of Monocotyledonous and Dicotyledonous Plants to Paracetamol Exposure

VII. RESEARCH GAPS AND FUTURE PERSPECTIVES

Although attention to pharmaceuticals as emerging environmental contaminants has increased, important gaps remain in understanding their effects on plants, particularly during early development. Much of the existing research has focused on the occurrence, environmental fate, and removal of pharmaceutical residues from wastewater, whereas comparatively less attention has been directed toward their biological effects on terrestrial plants and crops (Carvalho et al., 2014; Wei et al., 2023).

A major limitation is the relatively narrow range of pharmaceutical–plant combinations investigated. Plant responses can vary by species, pharmaceutical characteristics, concentration, and exposure duration. For example, paracetamol exposure significantly inhibited root and shoot elongation in wheat, while germination remained unaffected under the tested conditions (An et al., 2009). Similarly, studies using *Lactuca sativa* have demonstrated that different pharmaceuticals may produce distinct responses in germination and early growth (Pino et al., 2016). These observations indicate that findings obtained from one pharmaceutical or plant species cannot necessarily be generalized to other systems.

Another important gap concerns the distinction between germination and post-germination responses. Germination percentage is frequently used as a primary toxicity endpoint, but available evidence suggests that root and shoot development may respond even when germination remains relatively stable (An et al., 2009; Pino et al., 2016). Future investigations should therefore incorporate multiple endpoints, including germination rate, root and shoot elongation, seedling biomass, chlorophyll content and selected biochemical or oxidative-stress indicators.

More systematic concentration–response and exposure-duration studies are also needed. Investigations using multiple concentrations can help distinguish threshold, sublethal, and inhibitory responses, while longer exposure periods may reveal effects not apparent during short-term experiments. Furthermore, environmentally realistic concentrations and exposure scenarios should receive greater attention to improve the ecological relevance of laboratory findings (Wei et al., 2023).

Comparative studies involving monocotyledonous and dicotyledonous species represent another useful research direction. However, differences observed between individual species should not automatically be interpreted as a general monocot–dicot pattern. The source material similarly identifies the need for broader comparative studies across plant species and concentrations.

Future research should therefore integrate multiple plant species, concentration ranges, exposure durations, and developmental endpoints, while also considering pharmaceutical mixtures and environmentally relevant exposure conditions. Such approaches would provide a more comprehensive understanding of the potential ecological implications of pharmaceutical contamination on early plant development.

VIII. CONCLUSION

Pharmaceutical residues represent an emerging environmental concern because their continuous release through wastewater, industrial discharges, improper disposal, and wastewater reuse can result in repeated exposure of non-target organisms. Among these contaminants, paracetamol provides a relevant example of how a commonly used pharmaceutical may influence early plant development. Available evidence indicates that its effects are not necessarily uniform across developmental stages.

In particular, studies on wheat have demonstrated that increasing paracetamol concentrations can significantly reduce root and shoot elongation, while seed germination may remain unaffected under the tested conditions. This distinction highlights the importance of evaluating post-germination growth rather than relying exclusively on germination percentage as an indicator of pharmaceutical phytotoxicity.

The reviewed evidence also indicates that plant responses depend on pharmaceutical concentration, exposure duration, and species-specific characteristics. Physiological and biochemical changes, including alterations in chlorophyll, soluble proteins, and antioxidant enzyme activity, may accompany morphological responses. However, available studies are insufficient to establish a universal response pattern for either monocotyledonous or dicotyledonous plants.

Overall, the evidence supports using germination, root and shoot growth, and selected physiological or biochemical parameters as complementary endpoints for evaluating pharmaceutical effects on plants. Future research should emphasize comparative studies involving multiple plant species, environmentally relevant concentrations, different exposure durations, and, where appropriate, pharmaceutical mixtures. Such investigations will improve understanding of how pharmaceutical contamination may influence early plant development and help clarify its broader environmental significance.

REFERENCES

- [1] J. An, Q. Zhou, F. Sun, and L. Zhang, "Ecotoxicological effects of paracetamol on seed germination and seedling development of wheat (*Triticum aestivum* L.)," *Journal of Hazardous Materials*, vol. 169, no. 1–3, pp. 751–757, 2009, doi: 10.1016/j.jhazmat.2009.04.011.
- [2] K. Balakrishna, A. Rath, Y. Praveenkumarreddy, K. S. Guruge, and B. Subedi, "A review of the occurrence of pharmaceuticals and personal care products in Indian water bodies," *Ecotoxicology and Environmental Safety*, vol. 137, pp. 113–120, 2017, doi: 10.1016/j.ecoenv.2016.11.014.
- [3] P. N. Carvalho, M. C. P. Basto, C. M. R. Almeida, and H. Brix, "A review of plant-pharmaceutical interactions: From uptake and effects in crop plants to phytoremediation in constructed wetlands," *Environmental Science and Pollution Research*, vol. 21, pp. 11729–11763, 2014, doi: 10.1007/s11356-014-2550-3.
- [4] A.-L. Garduño-Jiménez and L. J. Carter, "Insights into mode of action mediated responses following pharmaceutical uptake and accumulation in plants," *Frontiers in Agronomy*, vol. 5, Art. no. 1293555, 2024, doi: 10.3389/fagro.2023.1293555.
- [5] N. Kaur, T. E. Erickson, A. S. Ball, and M. H. Ryan, "A review of germination and early growth as a proxy for plant fitness under petrogenic contamination—Knowledge gaps and recommendations," *Science of the Total Environment*, vols. 603–604, pp. 728–744, 2017, doi: 10.1016/j.scitotenv.2017.02.179.
- [6] J. Kudrna, F. Hnilicka, J. Kubes, P. Vachova, H. Hnilickova, and M. Kuklova, "Effect of acetaminophen (APAP) on physiological indicators in *Lactuca sativa*," *Life*, vol. 10, no. 11, Art. no. 303, 2020, doi: 10.3390/life10110303.
- [7] M. Kummerová, Š. Zezulka, P. Babula, and J. Triska, "Possible ecological risk of two pharmaceuticals diclofenac and paracetamol demonstrated on a model plant *Lemna minor*," *Journal of Hazardous Materials*, vol. 302, pp. 351–361, 2016, doi: 10.1016/j.jhazmat.2015.09.057.
- [8] B. Pawłowska and R. Biczak, "Drugs in the environment—Impact on plants: A review," *Environmental Toxicology and Pharmacology*, vol. 111, Art. no. 104557, 2024, doi: 10.1016/j.etap.2024.104557.
- [9] M. R. Pino, S. Muñoz, J. Val, and E. Navarro, "Phytotoxicity of 15 common pharmaceuticals on the germination of *Lactuca sativa* and photosynthesis of *Chlamydomonas reinhardtii*," *Environmental Science and Pollution Research*, vol. 23, no. 22, pp. 22530–22541, 2016, doi: 10.1007/s11356-016-7446-y.
- [10] N. Ranjan, P. K. Singh, and N. S. Maurya, "Pharmaceuticals in water as emerging pollutants for river health: A critical review under Indian conditions," *Ecotoxicology and Environmental Safety*, vol. 247, Art. no. 114220, 2022, doi: 10.1016/j.ecoenv.2022.114220.
- [11] D. Rede, L. H. M. L. M. Santos, S. Ramos, F. Oliva-Teles, C. Antão, S. R. Sousa, and C. Delerue-Matos, "Individual and mixture toxicity evaluation of three pharmaceuticals to the germination and growth of *Lactuca sativa* seeds," *Science of the Total Environment*, vol. 673, pp. 102–109, 2019, doi: 10.1016/j.scitotenv.2019.03.432.
- [12] J. Rivera-Utrilla, M. Sánchez-Polo, M. Á. Ferro-García, G. Prados-Joya, and R. Ocampo-Pérez, "Pharmaceuticals as emerging contaminants and their removal from water: A review," *Chemosphere*, vol. 93, no. 7, pp. 1268–1287, 2013, doi: 10.1016/j.chemosphere.2013.07.059.
- [13] S. A. Salazar Mercado and D. G. Vega Galvis, "Paracetamol ecotoxicological bioassay using the bioindicators *Lens culinaris* Med. and *Pisum sativum* L.," *Environmental Science and Pollution Research*, vol. 30, no. 22, pp. 61965–61976, 2023, doi: 10.1007/s11356-023-26475-7.

- [14] X. Hu, Q. Zhou, and Y. Luo, "Root uptake of pharmaceuticals and personal care product ingredients," *Environmental Science & Technology*, vol. 50, no. 2, pp. 525–541, 2015, doi: 10.1021/acs.est.5b01546.
- [15] H. Wei, M. Tang, and X. Xu, "Mechanism of uptake, accumulation, transport, metabolism and phytotoxic effects of pharmaceuticals and personal care products within plants: A review," *Science of the Total Environment*, vol. 892, Art. no. 164413, 2023, doi: 10.1016/j.scitotenv.2023.164413.
- [16] Š. Zezulka, M. Kummerová, P. Babula, M. Hájková, and M. Oravec, "Sensitivity of physiological and biochemical endpoints in early ontogenetic stages of crops under diclofenac and paracetamol treatments," *Environmental Science and Pollution Research*, vol. 26, no. 4, pp. 3965–3979, 2019, doi: 10.1007/s11356-018-3930-x.