

Phytoremediation of S-Triazine Herbicides: A Review

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Abstract

S-triazine herbicides such as atrazine, simazine, propazine, ametryn, and prometryn are among the most extensively used agrochemicals for controlling broadleaf and grassy weeds. Their persistence, poor biodegradability, and leaching potential have led to widespread contamination of soils and aquatic ecosystems, posing risks to human health and biodiversity. Phytoremediation, a plant-based in situ cleanup strategy, has emerged as an effective, low-cost, and environmentally friendly alternative to conventional remediation methods.

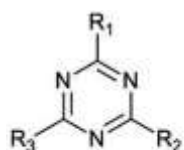
This review highlights the chemical properties, environmental behavior, and toxicity of S-triazine herbicides, followed by an overview of phytoremediation mechanisms such as phytoextraction, rhizofiltration, phytostabilization, phytodegradation, phytovolatilization, and rhizodegradation. Case studies on atrazine, simazine, ametryn, propazine, and prometryn show the potential of diverse terrestrial, aquatic, and transgenic plants—including maize, wetland macrophytes, and CYP1A2-expressing *Arabidopsis thaliana*—in removing or degrading these herbicides from contaminated media.

Factors affecting phytoremediation efficiency, as well as its advantages and limitations, are also discussed. Collectively, the evidence underscores the promise of phytoremediation as a sustainable approach for mitigating the environmental impacts of S-triazine herbicides, while identifying future directions for improving plant-based cleanup technologies.

1. Introduction

S-Triazine Herbicide

One type of environmental pollution is herbicides. They are selective, killing undesired plant matrices while mostly untouched by the intended crop. S-Triazine is a herbicide family that includes 1, 3, 5 s-triazine. The S-triazine molecule has a six-membered heterocyclic ring with alternating carbon and nitrogen atoms connected by double bonds as its main structural component. S-triazine herbicides have been widely used in agriculture to suppress grassy and broadleaf weeds in maize, sorghum, and sugarcane crops. S-triazine herbicides are widely used in many nations, posing environmental and health risks. Surface- and groundwater pollution in a number of nations is a result of the migration of s-triazine in soil.

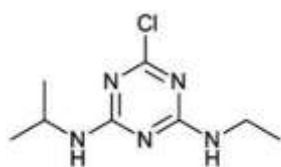


s-Triazine

(Medhat Rehan, Aml El sharkawy, Gomaah El Fadly, 2016)

Triazine herbicides are most frequently found in a class known as 1,3,5-triazines, also known as symmetrical triazines (s-triazines), which have three carbon and three nitrogen atoms arranged alternately on a planar 6-membered ring. (Saka M et al,2018) Simazine, atrazine, propazine, terbutryn are some of them. (Stara A et al,2012)

Atrazine (ATZ) is the most commonly used s-triazine herbicide. ATZ has been discovered to be persistent in soils due to its poor biodegradability and high sorption.(Chen L, Hu X,et al, 2018) Atrazine blocks quinone binding and inhibits photosynthesis by disrupting electron transport. (Esquirol L, Peat TS, et al, 2020)

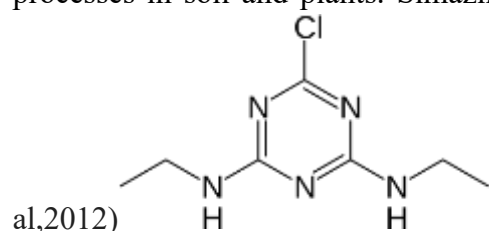


Atrazine

(Medhat Rehan, Aml El sharkawy, Gomaah El Fadly, 2016)

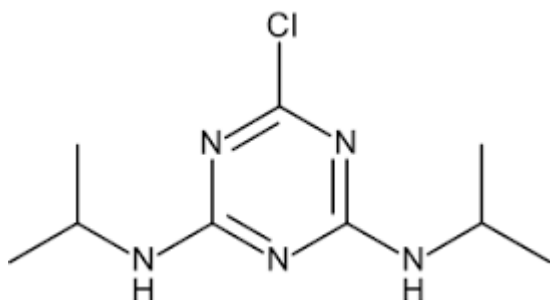
Atrazine was initially introduced in the 20th century and is frequently combined with other herbicides or used alone in agricultural applications. With an annual use of between 70,000 and 90,000 tonnes, it is the second most extensively used insecticide in the world. Atrazine is consumed in India on a yearly basis in amounts of 340 tonnes. (Simranjeet Singh et al, 2018)

One of the earliest compound triazines was simazine, (6-chloro-N2, N4-diethyl-1,3,5-triazine-2,4-diamine). It has a melting point of 226 °C and is a white, crystalline solid that is only slightly soluble in water but extensively soluble in organic solvents. It is biodegradable and is broken down by chemical and microbial processes in soil and plants. Simazine has a moderate soil persistence range of 28–149 days. (Stara A et



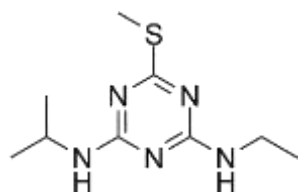
Simazine

Different crops of economic significance have been treated with the propazine herbicide all over the world. Propazine is frequently detected in water bodies in numerous nations beyond the permitted amounts because of its recalcitrance and leaching potential.(Pereira AR et al,2016) During the cultivation of milo grain sorghum, the triazine herbicide propazine (2-chloro-4,6-diisopropylamino-1,3,5-triazine) is used to suppress annual grasses and broadleaf weeds.(Gholivand MB et al,2012)



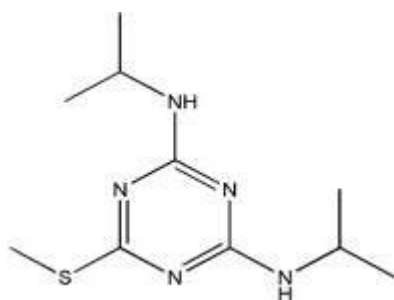
Propazine

In fields of sugarcane, bananas, maize, and pineapples, ametryn [2-(ethylamino)-4-isopropylamino-6-methylthio-s-triazine] is a second generation herbicide used to manage annual grasses and broadleaf weeds. Additionally, it is used in potato fields to reduce general weed. It is harmful to humans and can cause cancer, muscular weakness, nausea, vomiting, and diarrhoea. Additionally, it irritates the skin, eyes, and respiratory system. Additionally, both aquatic and land species are poisoned by it. (Ali I et al,2006)



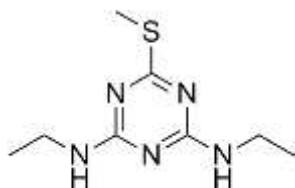
Ametryn

The 1,3,5-triazine family member prometryn [2-(methylthio)-4,6-bis(isopropylamino)-s-triazine] is registered for use in cotton, celery, and pigeon pea and is advised for the control of grasses and broad-leaf weeds in vegetable crops.(Wang Y et al, 2014)



Prometryn (Wang Y et al, 2014)

Similar in biological qualities to Atr, simetryn [N2,N4-diethyl-6-methylsulfanyl-1,3,5-triazine-2,4-diamine] is another commonly used herbicide. Prometryn and Simetryn were developed in the late 1960s as an alternative to short-acting herbicides, but due to their widespread usage, they are now perhaps the most significant contributors of pesticide-related environmental water pollution in various nations. Both substances are white crystalline solids with half-lives of around one to two months and low to moderate water solubilities (33 and 450 mg/L, respectively). (Bonora S et al, 2013)



Simetryn (Bonora S et al, 2013)

The general name "phytoremediation" is made up of the Latin root *remedium* and the Greek prefix *phyto* (plant).

A technique for in-situ cleanup called phytoremediation makes use of the natural skills of live plants. It is also a clean-up technique that uses solar energy and is environmentally benign, built on the idea of utilising nature to purify nature. Since 1991, the practice of using plants to lessen the quantity, mobility, or toxicity of pollutants in soil, groundwater, or other polluted media has been referred to as phytoremediation. (Etim EE, 2012)

A innovative, less expensive, effective, environmentally and environmentally friendly remediation approach with high public support is phytoremediation. (Moosavi SG, Seghatoleslami MJ, 2013)

Using different plants to remove, degrade, contain, or immobilise pollutants from soil and water is a new method called phytoremediation. Recently, this technology has drawn attention as a creative, economical substitute for the more traditional treatment techniques employed at hazardous waste sites. Academic and industry experts have generally regarded plant-based environmental remediation technology as a sustainable cleanup method that may be used in both developed and developing countries. (Sharma P and Pandey S, 2014)

2. Mechanisms of Phytoremediation

In addition to creating biomass, plants have the ability to take in, degrade, convert, and sequester pollutants. The parameters of the site and, primarily, the kind of contamination, determine the length of phytoremediation, the type, and the necessary number of species. (Boroş MN et al, 2014)

Plant-based soil remediation techniques may be thought of as biological treatment methods with a vast, self-expanding absorption network (the root system) that improves the ecosystem below the surface for later productive usage. The use of phytoremediation reduces the danger of contamination spreading by avoiding excavation and transfer of contaminated media. It also has the ability to clean up areas that have been contaminated by many pollutant types. (Sharma P and Pandey S, 2014)

Phytoextraction

The term "phytoextraction" describes the transfer of pollutants from soil or water to any harvestable plant portion by plant roots. The removal of pollutants and long-term remediation of soil or wastewater are both

possible with phytoextraction. The effectiveness of phytoextraction as a possible method for cleaning up the environment depends on a number of variables, including the availability of metals for absorption and the capacity of plants to take up and store metals in aerial portions. (Bhargava A et al, 2012)

Rhizofiltration

Rhizofiltration utilises plant roots to concentrate and precipitate pollutants on or within the root. It works by adsorbing them from the surrounding root zone (rhizosphere). Exudates from the roots of plants, or secondary metabolites, are subject to biogeochemical reactions that might precipitate pollutants on the roots or into the water body. Then, depending on the kind of plant, the species and concentration of the contaminant, the adsorption of pollutants on the roots, inside the roots, or transfer to the phyllosphere (plant organs above-ground), will take place. (Kristanti RA et al, 2021)

Phytovolatilization

Volatilization from the plant, also known as phytovolatilization, can be a significant loss mechanism for volatile and semi-volatile organic compounds (VOCs). Since phytovolatilization of the pollutant typically results in significant dilution and photochemical degradation in the atmosphere, it is frequently seen as advantageous. Numerous pollutants, both inorganic and organic, have been widely reported to undergo phytovolatilization. (Limmer M et al, 2016)

Phytostabilization

One of the phytoremediation methods for polluted soil is phytostabilization. The stabilisation of soil pollutants by the joint influence of root exudates and related microorganisms is presented as the essential mechanism for this method. According to a decrease in the migration of pollutants into deeper soil, groundwater, plants, and the food chain, it might lessen the damage that pollutants do to the environment and organisms. By releasing root exudates that contain bioactive substances like organic acids, amino acids, proteins, sterols, and other compounds with various chemical groups, the plant can also control the environmental behaviour or bioavailability of contaminants as well as improve the metabolic capabilities of the microorganism in rhizosphere soil. (Cao B et al, 2018)

Phytodegradation

Complex organic compounds are either broken down into simpler molecules or incorporated into plant tissues. When the photodegradation system is in action, pollutants are degraded after being absorbed by the plant. Plant absorption often only happens when the pollutants' solubility and hydrophobicity fall below a specific permissible range, just like with phytoextraction and phytovolatilization. It has been shown that photodegradation may remove certain organic pollutants from soil, sediment, or groundwater, including herbicides, chlorinated solvents, and munitions. (Etim EE, 2012)

Rhizodegradation

A possible remediation solution for organic contaminants in soil is rhizodegradation. In order to clean up the surrounding soil, this type of phytoremediation makes use of the organic interactions between plants

and rhizosphere microorganisms. (Ely CS and Smets BF, 2017) Around the root, the rhizosphere extends for about 1 mm and is influenced by the plant (Pilon-Smits, 2005). The growth in the quantity and metabolic activity of the microorganisms is probably the primary factor causing the improved breakdown of contaminants in the rhizosphere. (Ali H et al., 2013)

3. Advantages of Phytoremediation

The cost of phytoremediation varies greatly, and there is a strong association between the cost of phytotreatment and the concentration, kinds, soil and/or water qualities, site conditions, and significance of the pollutant as a potential threat to the food chain. In any case, phytoremediation is one of the most economically advantageous treatment options with widespread societal support. (Farraji H et al., 2016)

Through the use of the In Situ approach, it limits the spread of toxins to other, untouched settings. Similar to conventional techniques of pollutant removal, phytoremediation causes only minimal soil disturbance. It is used in any environment that has been polluted by organic or inorganic composites. (Galadima AI et al., 2018)

Other advantages:

- All organic and inorganic materials are included.
- Metals should be kept both in and out of place.
- No more harm to the soil's structure than with current techniques.
- Maintaining them prevents water and wind flow transfers from being eroded.
- With highly skilled individuals, significant equipment is not necessary.

4. Disadvantages of Phytoremediation

Any impairment, failure, or unanticipated reaction might change as a factor affecting plant species and could also increase the drawbacks of phytoremediation. (Farraji H et al., 2016) requires safe disposal of the harvested plant after treatment. It is only permitted in less contaminated settings. The effectiveness of the approaches is significantly affected by temperature and other environmental factors. (Galadima AI et al., 2018)

Pollutant buildup in fruits, vegetables, and other edible crop portions; very gradual and seasonally effective treatment procedure. The primary environmental impact of this green technology is the handling and disposal of polluted plants through phytoremediation. Water-soluble contaminants are not good candidates for aquatic phytoremediation. (Farraji H et al., 2016)

Worldwide ecological concern is caused by arboricultural contamination. The intensive use of cultivating

inputs, such as pesticides and manures, and cultivating techniques is what mostly causes agrarian pollution (e.g., spillover & remotest culturing of the land).

Arable imperfections might include necessary plant fortifications (such as excessive amounts of phosphate and nitrate), hazardous inorganics (such as heavy metals), and natural mixtures (e.g., pesticides).

Pesticide pollution in the environment poses a real threat to people as well as other marine and terrestrial species. If not controlled, the pollution can prompt difficult issues to the climate. Some viable and cost-effective alternative approaches are needed to maintain this emission at a low level. Remediation techniques, such as phytoremediation and microbial remediation, are effective approaches that use plants and organisms to exclude atmospheric acaricide scrapings. These techniques offer effective and powerful substitutes that are more controllable from a financial and environmental standpoint than chemical and physical remediation procedures.

Therefore, the removal of such hazardous compounds is crucial for both the biological system's protection and human welfare. Phytoremediation is a practical method for eliminating agricultural toxins and comes with an excellent guarantee for purifying contaminated soil and water. Although harmful horticulture contaminations can be removed by plants alone using a variety of techniques, coordinated techniques, such as organisms and plant affiliations (rhizoremediation), have appeared to be attractive options for enhancing the expulsion of agricultural poisons. (Manmeet Kaur, Et al, 2022).

Since the introduction of man made herbicide S-triazine such as atrazine, simazine, cyanazine, ametryn, metribuzin etc. these have been used enormously in controlling broadleaf weed growth among different crop plants, thus by improving the quality and yield of the crop. Atrazine is most extensively used to control weeds in crops like sorghum and corn. Herbicides are important but the destruction caused by them discombobulates the surrounding environment. Transgenic plants are often used for phytoremediation to metabolize the foreign chemicals used to reduce weed infestation. Herbicides belonging to S

-triazine are found to be carcinogenic to human cells. Thus, the degradation of these enzymes becomes quite important (Nikolina Udikovic-kolic, Et al 2012).

Phytoremediation of atrazine contaminated soil

1. Using *zea mays* (maize)

In greenhouse studies, the potential of maize plants to clean up atrazine contaminated soil was investigated. Atrazine (Gesaprim 90 percent WG) was applied to the potted sandy loam soil at concentrations of

0.5 and 1.0 ppm before maize was planted there right away. Maize plants were cut and thrown away after 15, 30, 45, and 60 days from seeding. To find atrazine residues, wheat seeds were sowed in soil that had been treated.

The controls were untreated soil and soil that had not been planted with maize. The shoot and root lengths of wheat seedlings were measured seven days after seeding. According to the findings, the treated soil

that had already been planted with maize had taller shoot and root lengths of wheat than the treated soil that had not yet been planted.

Introduction

Many of these chemicals enter the soil and remain there for extended periods of time, causing harm to living things. Herbicide use for both agricultural and non-agricultural uses results in severe environmental contamination on a global scale. To clean up this pollution, sustainable and environmentally friendly procedures must be developed. A method called phytoremediation has the

potential to help restore damaged soil. According to Yao et al. (2009), phytoremediation is a technique for using plants to remove contaminants from the environment. The benefits of phyto-remediation are low cost, resource conservation, and the absence of secondary pollutants. Therefore, phytoremediation of polluted soils has a promising future.

The effect of atrazine residues in soil on wheat

50 g of soil were taken from each treatment's replicate (50 g/replicate) and placed in plastic pots measuring 5 by 7 cm. After each period of discarding the maize, as previously mentioned, four seeds of wheat were then planted in the plastic pots.

Pots were watered as needed and housed in a growth chamber at a temperature of 20 ± 2 °C. After 7 days, the wheat plants' shoot and root lengths were measured. The recorded data were utilised as criteria to compare the herbicide's phytotoxicity to sensitive plants as a sign of the herbicide's presence in the soil when there were no tolerant plants present when there were evaluation of soil atrazine residues samples of soil.

Results and analysis

1. Phytotoxicity

Results in Table 1 generally demonstrated that atrazine harmed plant roots more than shoots, as shown by EC₅₀ values. Among the other plants employed, maize had the highest atrazine tolerance. For the maize shoot and root, the EC₅₀ values for atrazine were 20.24 and 15.42 ppm, respectively.

Wheat, on the other hand, was a very sensitive plant to atrazine; its respective EC₅₀ values for the shoot and root were 0.01 and 0.02 ppm. This indicates that maize was 2024 (=20.24/0.01) times more resistant to atrazine than wheat. Maize, bitter lupine, sweet sorghum, radish, sweet lupine, oat, soy bean, and wheat were the plants that tolerated atrazine the least.

Table 1. Effect of [atrazine](#) on shoot and root lengths (cm) of different seedlings after 7 day-period of application in water agar medium.

Plants	EC ₅₀ ^a (ppm)	
	Shoot	Root
Empty Cell		
Wheat	0.01	0.02
Soya bean	0.14	0.30
Oat	1.83	0.61
Sweet lupine	3.88	2.08
Radish	8.22	4.73
Sweet sorghum	13.12	11.15
Bitter lupine	14.72	11.10
Maize	20.24	15.42

EC₅₀: Effective concentration of herbicide that gives 50% reduction of shoot or root lengths of plants.

As a result, we used maize to phytoremediate soil that had been poisoned with the herbicide under test. However, in order to identify herbicide residues in polluted soil, wheat was employed as the most sensitive plant.

The capacity of plants to detoxify herbicides, which depends on the availability of specific detoxification enzymes such as cytochrome P-450s and glutathione-S-transferases, may be connected to their tolerance to herbicides. Nemat Alla (2000) noted that an increase in GST along with a decrease in herbicide residues in maize led to a faster rate of their detoxification.

Also, Belford et al. (2004) showed that cytochrome P-450s and glutathione-S-transferases constitute two of the largest groups of enzyme families that are responsible for detoxification of exogenous molecules in plants. (S.I. Ibrahim Et al, 2013)

2. By three emergent hydrophytes

Three emergent hydrophytes, *Iris pseudocorus*, *Lythrum salicaria*, and *Acorus calamus*, were tested in a hydroponic system for atrazine (ATZ) elimination and uptake in order to assess their potential as phytoremediation agents for ATZ-contaminated water. The relative growth rate of plants in sterile circumstances was lower than in natural settings after 20 days of exposure.

ATZ removal rates in natural conditions were higher than in sterile conditions ($p < 0.05$), and the amount of ATZ in a culture solution planted with emergent plants was reduced significantly as compared to an unplanted solution.

I. pseudacorus, *L. salicaria*, and *A. calamus* each contributed 75.6, 65.5, and 61.8 percent of the degradation, respectively. These proportions corresponded to 5.4, 11.4, and 17.4 percent of the solution's equivalent microbial population.

Emergent plants are primarily responsible for decreasing the concentration of ATZ in the water body and serving as phytoremediation agents. (Qinghai Wang, Et al, 2012)

3. By three species of wetland plant

In this study, wetland plants were evaluated for their ability to phytoremediate atrazine in an aquatic setting. Three plant species—*sweet flag*, *broadleaf cattail*, and *narrow-leaf cattail*—had their atrazine concentration and biomass changes examined. The elimination of atrazine and changes in plant biomass were evaluated. Two mathematical models were created to represent atrazine

toxicity toward the investigated plant species and atrazine fate during long-term phytoremediation. The atrazine tolerance and atrazine elimination rate that Sweet Flag demonstrated were just the greatest.

Atrazine's typical half-life was drastically shortened from 400 days to just 5 days. The atrazine concentration had decreased by more than 99 percent from the highest tested starting concentration (20 mg/l) after 40 days. (Roman Marecik, Et all, 2012)

4. By *Potamogeton crispus* and *Myriophyllum spicatum*

One of the pesticides that is most frequently seen is atrazine, which is extremely dangerous to both people and the environment. This study assessed how *Potamogeton crispus* and *Myriophyllum spicatum*, two submerged

macrophytes, affected the phytoremediation of atrazine. The findings indicated that over the course of the experiment's 60 days, atrazine degraded more quickly in the pots containing these two plants than it did in the

control without them. Atrazine was mostly transformed into hydroxyatrazine and diaminochlorotriazine, according to investigations of its metabolites.

Atrazine's dissipation kinetics and risk evaluation revealed that at the recommended high dosage, atrazine degraded quite quickly in maize and was generally safe for consumption by humans.

Atrazine's maximum permitted intake (MPI) was determined to be 0.23 for a kid, and 0.72 g per person every day for an adult.

Atrazine residue still poses a serious threat to the environment due to the widespread use of atrazine over the years. Atrazine could be removed from contaminated sediment and water by employing the submerged macrophytes

M. spicatum and *P. crispus*. A technique for assessing submerged plants in pesticide absorption or phytoremediation was devised by this study.

P. crispus and M. spicatum

P. crispus and *M. spicatum* were grown in pot experiments using silt from Lake Yuehu in order to demonstrate their potential for phytoremediation of atrazine. Atrazine was added to the surrounding water in one experiment to obtain the desired concentration of 40 g/L. At various times, the levels of atrazine in the surrounding water, sediment, and plants were analysed.

Atrazine was added to the sediment in the second experiment to obtain the desired concentration of 200 g/kg. The levels of atrazine in the surrounding water, sediment, and plants were also measured at various times. For ease of sampling, a set of 10 g sediment samples were placed inside each 300-m nylon mesh bag.

P. crispus and *M. spicatum* plants were likewise individually contained in a 300-m nylon mesh in a similar manner. A total of 15 plants were grown in each container. Water and sediment samples were taken during each experiment on days 2, 5, 10, 15, 20, 25, 30, 40, and 60, respectively. Specifically, plant samples were taken on days 20, 40, and 60.

Prior to analysis, all samples were stored at 20°C. To test the plants' resistance to atrazine, one control group was created in which the pots received no atrazine treatment. A different control group, in which no plants were grown in the pots, was created to evaluate the atrazine's absorption by the plants.

Results

Atrazine toxicity tolerance of macrophytes

Findings indicate that on day 20 following the application of atrazine, neither plant was harmed. *P. crispus* was relatively more resistant to atrazine than *M. spicatum*.

At the end of the experiments on day 60, the leaves of *M. spicatum* turned completely dark, while only about 60% and 20% of *P. crispus* turned dark in the experiments where atrazine was 6 H. LI ET AL. added to the sediment and the overlying water, respectively. *P. crispus* may be a better candidate for the phytoremediation programme for atrazine.

The macrophytes remove atrazine from the sediment or surrounding water and absorb it.

Atrazine was introduced to the surrounding water in our first experiment at a target concentration of 40 g/L. Atrazine levels in the surrounding water dramatically decreased on day 2 to concentrations of 11.4, 8.4, and 9.4 g/L for the experimental group containing *P. crispus* and *M. spicatum*, respectively (Figure 1(a)). According to Figure 1, the sediment's absorption was a major cause of the drop. Atrazine levels in the sediment dropped to 37.4, 23.8, and 32.1 g/kg on day 2 for the control group, the experiment group with *P. crispus*,

and the experiment group with *M. spicatum*, respectively. Atrazine concentrations in the control experiments were higher than those in the experiments with the plants.

Overall, the presence of these plants has decreased the amount of atrazine in the sediment and the surrounding water. Atrazine was added to the sediment in the second set of experiments with a target concentration of 200 g/kg.

On day 2, we observed a dramatic decline in atrazine levels in the sediment, with concentrations of 65.4 g/L, 65.1 g/L, and 64.7 g/kg being found for the control group, the experimental group with *P. crispus*, and the experimental group with *M. spicatum*, respectively.

Indicating that atrazine in the sediment was reasonably mobile under the experimental conditions, the concentration of atrazine in the overlying water on day 2 was 14.2, 9.2, and 10.4 g/L for the control, *P. crispus*, and *M. spicatum*, respectively. (Huidong li, Et al, 2019)

Potential of three species of terrestrial plants for phytoremediation of atrazine, azoxystrobin, and imidacloprid

Pesticides can drift off-target, contaminating delicate water bodies and having a negative impact on the organisms that live there.

Pesticides can migrate off-target less frequently with the use of best management techniques, like the planting of vegetative buffer strips, and phytoremediation can accelerate compound decomposition.

Iris versicolor, *Andropogon virginicus*, and *Panicum virgatum* were planted on soil that had been treated with one of three regularly used pesticides in this study.

Plants were destructively harvested at 28, 56, and 112 days after treatment (DAT), and pesticide residue in soil and above- and below-ground vegetation was examined using high-performance liquid chromatography (HPLC).

I. versicolor was shown to lower more atrazine in soil compared to non-planted pots at 112 DAT by 58.7% with respect to the amount of pesticide discovered in planted pots compared to non-planted pots. *I. versicolor* was also the best in removing azoxystrobin from the soil at 112 DAT, reducing it by 86.9% in comparison to unplanted pots. When compared to unplanted pots, *I. versicolor* and *P. virgatum* lowered soil imidacloprid levels by 62.5 and 64.3 percent, respectively, at the same sampling time. This data backs up the suggestion to grow a variety of plant types to maximise phytoremediation abilities.

Although studies have shown that plants can remove manmade toxins from the environment, this approach is only long-term if native plants are employed since they require little care and are resistant to the chemicals that are applied. Numerous earlier research have found that fast-growing, hardy, tolerant of environmental conditions, and low-maintenance plants are common.

These plant species, however, are frequently regarded as invasive and/or weed-like and are not necessarily ideal for any location. The present research initiates a list of plant species which can be used within the southeastern United States and similar areas to phytoremediate commonly used pesticides atrazine,

azoxystrobin, and imidacloprid and prevent off-target movement. (Alayne M. McKnight , Et all, ,2021)

Phytoremediation of simazine-contaminated soil

1. By p450-1a2 transgenic *Arabidopsis thaliana* plants

In lab and greenhouse tests, the potential application of human P450-transgenic plants for phytoremediation of pesticide-contaminated soils was investigated. Many herbicides, insecticides, and industrial chemicals are metabolised by transgenic P450 CYP1A2 gene *Arabidopsis thaliana* plants. Regarding the herbicide simazine, the P450 isozymes CYP1A2 expressed in *A. thaliana* were investigated (SIM).

Sim added in plant growth medium or sprayed on foliar regions caused considerable resistance in transgenic *A. thaliana* plants expressing the CYP1A2 gene. The outcomes demonstrated that SIM had a negative impact on the wild type (WT) plants' primary root length as well as rosette diameter.

The experiment's SIM concentrations had no effect on the rosette diameter or primary root length in transgenic *A. thaliana* lines. According to the findings, CYP1A2 can be utilised as a selectable marker for plant transformation, enabling effective selection of transgenic lines in growth media and/or in plants grown in soil.

The non-transgenic *A. thaliana* plants were significantly harmed by dosages above 50 mol SIM treatments, whereas the transgenic *A. thaliana* plants showed healthy growth when exposed to doses up to 250 mol SIM treatments. Environmental SIM pollutants can be removed using transgenic *A. thaliana* plants as phytoremediators.

Transformation in plant

A. thaliana plants underwent floral dip transformation in accordance with Clough and Bent's (1998) instructions. In a nutshell, *A. thaliana* plants were grown under conditions of short days (8h light and 20–22°C in the dark for 16 hours) to create biomass. Following that, plants were moved to long day blossoming (16 hours of sunshine and 8 hours of darkness at 23–25 °C). *Agrobacterium* containing the pTRA-K-CYP1A2 CYP1A2 expression construct was grown and *A. thaliana* plant blossoms were immersed in the *agrobacterium* solution for three to ten minutes.

In order to keep the humidity levels high, dipping plants were covered for a full night (16 hours). The vegetation was then switched to long-day growth conditions till seed harvesting and plant maturity. Plants used in physiological investigations were grown in growth chambers at 22 °C with a photon flux density of 100 mol m⁻² s⁻¹ under short-day conditions (8 h of illumination and 16 h of darkness).

Results

Transgenic arabidopsis plants were transformed and chosen.

Following the floral dip transformation methodology, the wild-type *Arabidopsis thaliana* plants were transformed with *A. tumefaciens* strain GV3101 harbouring the expression plasmid pTRAK-CYP1A2 (Figure 1A) (Clough and Bent, 1998). Three distinct *A. thaliana* lines that are transgenic for the CYP1A2 gene were created: CYP1A2-1, CYP1A2-2, and CYP1A2-3. Three CYP1A2 transgenic lines with positive signals were created and given the names CYP1A2-1, CYP1A2-2, and CYP1A2-3. Employment of WT control plants and the T2 generations of these transgenic lines for additional biochemical and molecular studies.

Effect of simazine on primary root length and rosette diameter of arabidopsis

Plant rosette diameter and primary plant root lengths were recorded for each genotype at all SIM concentrations. SIM herbicide has harmful effects on WT plants on both primary root length (Figure 2A) and rosette diameter (Figure 2B). About 67% reductions in primary root length parameters and 50% reductions in rosette diameter were obvious at SIM concentration of 1 μmol . Moreover, SIM concentrations above 1 μmol cause stunting of WT root and shoot growth (Figure 3). Plant rosette diameter and primary root length of transgenic

A. thaliana lines were completely not affected at all the used SIM concentrations up to 2 μmol . Only CYP1A2 transgenic lines with higher SIM concentrations than 10 mol showed gradual development retardation.

These findings suggest that the expression of the mammalian CYP1A2 gene improves the capacity of transgenic *A. thaliana* plants to detoxify and/or phytoremediate the toxic effects of SIM herbicide. Therefore, transferring mammalian CYP1A2 activity to crop plants could undoubtedly increase the plants' resistance to herbicides that include SIM.

After foliar spraying, simazine's impact on the development of wild-type and genetically modified Arabidopsis

The photosynthesis-inhibiting herbicide SIM clearly had a negative impact on the growth of WT plants cultivated in soil with various doses, as demonstrated by the germination tests used in this study. SIM dosages exceeding 50 mol per planting pot were sufficient to stall the plants' growth before killing them. In contrast, the applied SIM doses had no effect on the CYP1A2 transgenic *A. thaliana* plants.

When compared to WT plants, CYP1A2 plants develop and generate more leaves under SIM stress. For WT and transgenic *A. thaliana* plants that were allowed to grow either in MS media supplemented with varying SIM concentrations or sprayed with variable SIM concentrations, the LD50 for SIM phytotoxicity was calculated. For WT plants grown on MS media, the SIM LD50 was 0.35 mol.

However, the LD50 measurements for the CYP1A2-1, CYP1A2-2, and CYP1A2-3 transgenic lines were, respectively, 1.9, 1.5, and 2.5 mol SIM. It was calculated that the LD50 for WT

plants grown in soil and sprayed with various doses of SIM was around 15 mol. The LD50 values for CYP1A2 transgenic lines, in contrast to WT control plants, increased 10 to 16 fold. (Ehab Azab, Et al, 2016)

Phytoremediation of ametryn-contaminated soil

An extensive examination of the ametryn's breakdown and accumulation in soils and in plants such as wheat, maize, ryegrass, and alfalfa

Ametryn, a triazine-family selective herbicide, is used extensively in China and other parts of the world to eradicate annual weeds and grasses. There are, however, little publications on its environmental risk assessment with reference to contaminated soil and crops. In this study, ametryn residues in the soil around the plants' roots as well as ametryn accumulation in wheat, maize, ryegrass, and alfalfa crops were compared. We examined the enzyme activity in plant tissues, low molecular weight organic acids (LMWOAs), antioxidants, and degradation enzymes.

The shoots and roots of wheat and alfalfa contained the highest concentration of ametryn. The highest ametryn translocation factor (TF) from roots to shoots was found in ryegrass, with more than three times over the competition. Compared to soil planted with other plants, the ametryn residue in soil planted with ryegrass was significantly lower. The order of the residual ametryn content in soils used for crop planting was rhizosphere soil, bulk soil, non-rhizosphere soil, and control (without plants). Ametryn-exposed ryegrass had significantly increased catalase (CAT), glutathione S-transferase (GST), and laccase (LAC) activities than non-exposed ryegrass. In comparison to the control, the maximal CAT activities in the ryegrass shoot and root were raised 6.16- and 28.84-fold, respectively.

Ametryn caused the crop to exude organic acids, which greatly accelerated the herbicide's degradative process. The ability of ryegrass to remove ametryn from ametryn-contaminated soil and its plant tissues was therefore demonstrated to be relatively strong. (Ying Liu, Et al, June 2017) Phytoremediation of propazine-contaminated soil

Salicylic acid decreased the phytotoxicity of propazine on wheat, maize, and rapeseed.

Propazine is a common herbicide in the triazine family that is used on agriculture to grow crops. Recent research have demonstrated that propazine residue in the environment builds up over time. Propazine will certainly build up in crops as a result of this. Therefore, it is crucial to reduce the toxicity and buildup of propazine in crops. In this investigation, soil propazine concentrations of 2, 8 and 0.4 mg kg⁻¹ significantly reduced the development of wheat, maize, and rapeseed. While the electrolyte permeability, a diagnostic of cellular damage, increased in the plant cells, the chlorophyll content of the three crops likewise demonstrated a considerable drop. However, propazine phytotoxicity of the crops was alleviated by spraying plants with 5 mg L⁻¹ of salicylic acid (SA), increasing chlorophyll content and decreasing permeability of all crops to electrolytes.

Peroxidase (POD) and glutathione transferase (GST) activity, meanwhile, remained low. High performance liquid chromatography was used to measure the residues in the soil and the buildup of propazine in the crops. Propazine concentrations in soil and plants treated by SA were lower than those in the untreated control.

Using quadrupole-time-of-flight tandem mass spectrometry and ultraperformance liquid chromatography, six propazine degradation products (derivatives) in wheat rhizosphere were identified. Our research suggests that the faster breakdown of propazine by salicylic acid may have contributed to the improved crop growth. (Jing Jing Zhang , Et al, 2018)

Phytoremediation of Prometryn-contaminated soil

Hydroponic media are cleaned of prometryn using marsh pennywort (*Hydrocotyle vulgaris* L.) The ability of the aquatic plant *Hydrocotyle vulgaris* to remove prometryn from nutrient solution was examined. *H. vulgaris* was able to remove up to 94.0 percent of the original prometryn from the hydroponic culture medium in 30 days when experiment conditions were optimised. Prometryn's concentration dropped from 0.55 0.013 mg/L at the beginning of the trial to 0.036 0.001 mg/L at the conclusion.

The removal kinetics ($C_t = 0.4569e^{0.09t}$) were in accordance with the first-order kinetic equation. Prometryn's half-life ($t_{1/2}$) was reduced from 27.16 days (without plant) to 5.58 days (with *H. vulgaris*). In *H. vulgaris* tissue, there was around 22% of the original prometryn residue, and after 30 days, the plant had broken down 11.7% of it. After 30 days, the prometryn metabolites 2,4-diamino-1,3,5-triazine and 2,4,6-trihydroxy-1,3,5-triazine were found in the hydroponic culture medium and plant tissue, respectively. According to the findings, *H. vulgaris* can be utilised to phytoextract prometryn, and it may also be able to successfully eliminate additional s-triazine pesticides from contaminated aquatic habitats. (J.Ni, Et al, 2018)

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