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POSTGRADUATION PROGRAM IN MATERIALS SCIENCE

PEDRO HENRIQUE CORREIA DE LIMA

Lignin nanoparticles as sustainable carriers of herbicide: from development to effects in plants

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POSTGRADUATION PROGRAMM OF MATERIALS SCIENCE

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Thesis submitted to the Postgraduation Program in Materials Science of the Department of Physics and Chemistry of the São Paulo State University "Júlio de Mesquita Filho", School of Engineering, Ilha Solteira, as a requirement to obtain the title of Doctor in Materials Science.

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Advisor: Prof. Dr. Renato Grillo

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LIST OF ABREVIATIONS AND ACRONYMS

μ	Chemical potential
AL	Alkali Lignin
ATZ	Atrazine
BB	Bibenzyl
C	Concentration
CA	Citric acid
CAT	Catalase
CMC	Carboxymethyl cellulose
CNC	Cellulose nanocrystals
CNFs	Cellulose nanofibers
DCMC	Dialdehyde carboxymethyl cellulose
DFT	Density functional theory
DLS	Dynamic Light Scattering
DTT	Dithiothreitol
EDS	Energy dispersive spectroscopy
EE	Encapsulation efficiency
ENPs	Engineered nanoparticles
FCI	Falker chlorophyll index
FTIR	Fourier transform infrared spectroscopy
GADPH	Glyceraldehyde 3-phosphate dehydrogenase
GLY	Glycine methyl ester
GMA	Glycidyl methacrylate
GST	Glutathione S-transferases
H_2O_2	Hydrogen peroxide
HCl	Hydrochloric acid
HOMO	Highest occupied molecular orbital
I_2	Iodine

K Release rate Constant

KBr Potassium Bromide

KI Iodine Potassium

LDH Layered double hydroxides

LUMO Lowest unoccupied molecular orbital

MDA Malondialdehyde

Mo Mass of atrazine in the interval t

MTZ Metribuzin

η Chemical hardness

NBT Nitro Blue Tetrazolium

NTA Nanoparticles tracking analysis

PCL Polycaprolactone

PdI Polydispersity Index

PEG Polyethyleneglycol

PER Peroxidase

pH Hydrogen potential

PHFBA Poly 2,2,3,4,4,4-hexafluorobutyl methacrylate

PHR Phosphate starvation response

POD Guaiacol peroxidase

PPE 2- phenethyl phenyl ether

PVP Polyvinylpyrrolidone

ROS Reactive oxygen species

RT-qPCR Reverse transcription - quantitative polymerase chain reaction

S Chemical softness

SDGs Sustainable Development Goals

SEM Scanning electron microscopy

SEM/EDS Scanning Electron Microscopy with coupled energy dispersive spectroscopy

SLNPs Spherical lignin nanoparticles

SLNPs_ATZ Spherical lignin nanoparticles with atrazine

SOD	Superoxide dismutase
t	Time
TCA	Thiobarbituric acid
Td	Degradation temperature
TGA	Thermogravimetric analysis
UN	United Nations
UV-Vis	Ultraviolet-visible
Wf	Total weight
Wi	Initial weight
Ω	Electrophilicity index

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Gratefulness is a social responsibility, to make people happy and ignite the lightness in an exchange of gestures that touch magic. Being grateful for my mother is to be close to God. For my father, gratefulness comes with his affectionate gestures. Having them both is enough for me to be grateful.

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RESUMO

Por décadas, os agricultores têm tentado controlar as plantas daninhas e aumentar a produtividade das colheitas para fornecer alimentos para uma crescente população através do uso de herbicidas. A modernidade através da nanociência auxilia a diminuição da quantidade dos herbicidas através de nanocarreadores inorgânicos, híbridos e orgânicos (ou nanoherbicidas) no campo experimental. Nesse contexto, nanocarreadores orgânicos provindos de material lignocelulósico surgem como candidatos promissores, destacando-se a lignina: encontrada em plantas, é um resíduo agrícola cuja estrutura polifenólica pode formar (núcleos hidrofóbicos/cascas hidrofílicas) nanoestruturas que podem interagir com herbicidas como a atrazina e liberar lentamente esse bioativo. Assim, a presente Tese teve como objetivo principal discutir sobre nanocarreadores constituídos de materiais lignocelulósicos para liberação de agroquímicos, bem como desenvolver nanopartículas esféricas de lignina (SLNPs) com o herbicida atrazina (SLNPs_ATZ) a fim de se compreender os seus efeitos em organismos alvo e não alvo. As nanopartículas foram fabricadas pelo método de precipitação antissolvente e caracterizadas por TGA, FTIR, MEV/EDS, DLS, NTA, espectroscopia UV-VIS. SLNPs apresentaram morfologia esférica e distribuição de tamanho de 145 ± 45 ~ 178.9 ± 60.88 nm sem ATZ e 136 ± 43 ~ 268.2 ± 69.58 nm com ATZ e eficiência de encapsulação de 74,2 %. Testes de liberação foram feitos por espectroscopia UV-VIS e observou-se uma liberação de 43,26% de ATZ após 168 horas para SLNPs_ATZ, sendo Korsmeyes-peppas o modelo de liberação encontrado. Em paralelo, a Teoria do Funcional da Densidade (DFT) foi aplicada entre a atrazina e duas moléculas modelo de lignina apresentando energias de gap mais baixas quando as moléculas foram colocadas juntas, indicando uma forte interação entre lignina e atrazina. Além disso, o efeito das SLNPs com e sem ATZ foi avaliado em organismos não alvo. Assim, experimentos em hidroponia (escolhidos como meio inerte) foram realizados em alfaces lisas (*Lactuca sativa var. capitata*). Uma dose subletal de atrazina (30 µg/L) foi usada para manter as alfaces vivas por 28 dias a fim de observar potenciais alterações fisiológicos e bioquímicos nas plantas. Alfaces tratadas com SLNPs e SLNPs_ATZ não apresentaram alterações significativas no comprimento da raiz e na parte aérea quando comparadas ao controle, enquanto alfaces tratadas com ATZ apresentaram. Além disso, testes bioquímicos como enzimáticos (catalase-CAT, peroxidase de guaiacol - POD, superóxido dismutase - SOD e peroxidação lipídica - MDA) e expressão relativa de genes foram avaliados. MDA e CAT mostraram diferenças significativas comparando ATZ com todos os outros tratamentos. Pela expressão gênica, os genes CAT1 expressaram mais alto nas alfaces tratadas só SLNPs e ATZ pura, e os genes GST6 tiveram uma expressão mais alta com SLNPs. No entanto, alfaces tratadas com SLNPs apresentaram mais similaridades fisiológicas ao controle, indicando uma possível tolerância de alfaces quando interagem com SLNPs. Além disso, os genes PER51 apresentaram uma repressão em plantas tratadas com SLNPs_ATZ e ATZ (dano), e nenhuma alteração significativa com SLNPs quando comparado ao controle. Finalmente, sementes/mudas de plantas daninhas tiveram possíveis interferências na germinação/desenvolvimento quando tratadas com o nanoherbicida. Indicando a lignina como candidata sustentável para o preparo de nanocarreadores de herbicida, contribuindo para a. melhora da atividade herbicida em plantas, uma vez que mostrou possíveis alterações na expressão gênica e controle de plantas daninhas.

Palavras-chave: lignina, nanoherbicidas, atrazina, sustentável, plantas não-alvo e alvo.

ABSTRACT

For decades, farmers have been trying to control weeds and increase crop productivity to provide food for a growing population through the usage of herbicides, and nanoscience has been helping to reduce the quantity of herbicides through inorganic, hybrid, and organic nanocarriers (or nanoherbicides) in the experimental field. In this context, lignocellulosic organic nanocarriers emerge as promising candidates, and lignin standing out: found in plants, it is an agricultural residue whose polyphenolic structure can form (hydrophobic cores/hydrophilic shells) nanostructures that may interact with herbicides such as atrazine and slowly release this bioactive. Thus, the main objective of this thesis was to discuss nanocarriers made of lignocellulosic materials for agrochemicals release as well as to develop spherical lignin nanoparticles (SLNPs) with the herbicide atrazine (SLNPs_ATZ) to understand their effects on target and non-target organisms. The nanoparticles were manufactured by an antisolvent precipitation method and characterized by TG, FTIR, SEM/EDS, DLS, NTA, and UV-VIS spectroscopy. SLNPs presented spherical morphology and size distribution of 145 ± 45 ~ 178.9 ± 60.88 nm without ATZ, 136 ± 43 ~ 268.2 ± 69.58 nm with ATZ and loading efficiency of 74.2%. Release tests were performed by UV-VIS spectroscopy and a release of 43.26% of ATZ was found after 168 hours, with Korsmeyes-peppas as the release model. In parallel, Density Functional Theory (DFT) was applied among atrazine and two model lignin molecules and showed lower band gap energies when atrazine and lignin were placed together, indicating a strong interaction between molecules. Furthermore, the effect of SLNPs was evaluated in non-target organisms at hydroponic environment (chosen as inert medium) and lettuces (Lactuca sativa var. capitata) were selected to be the plant model. Sublethal doses of atrazine (30 µg/L) were managed to keep lettuces alive for 28 days and understand physiological and biochemical parameters. Lettuces treated with SLNPs and SLNPs_ATZ did not show significant changes in root and shoot length when compared to the control while lettuces treated with ATZ did. Then, biochemical tests such as enzymatic (catalase-CAT, guaiacol peroxidase - POD, superoxide dismutase - SOD, and lipid peroxidation - MDA) and relative gene expression were evaluated where MDA and CAT showed significant differences comparing ATZ with all other treatments. By gene expression, the CAT1 genes expressed higher in lettuces treated with SLNPs and ATZ, and the GST6 genes had a higher expression in those treated with SLNPs. However, lettuces treated with SLNPs showed less physiological changes compared to the control, indicating a possible tolerance of lettuce when interacting with SLNPs. In addition, the PER51 genes showed repression in plants treated with SLNPs_ATZ and ATZ (damage), and no significant change with SLNPs when compared to the control. Finally, weed seeds/seedlings had possible interferences in germination/development by nanoherbicide, indicating lignin as a sustainable molecule that in nanosphere forms can load atrazine and be effectively used in future experiments with non-target/target plants, showing possible results in gene expression and weed control.

Keywords: lignin, nanoherbicides, atrazine, sustainable, non-target and target plants.

SUMARY

GENERAL INTRODUCTION

The demand to increase the amount of food with sustainable processes while facing rapid population growth leads farmers and industries to search for new eco-friendly tools able to enhance harvest quality and reach the Sustainable Development Goals (SDG). Mainly, in the combat against weeds, plants unwilled in large crops (Darbyshire et al., 2024; Aijaz et al., 2025). Weeds disturb other plants by space, nutrients, water and light competition, reducing up to 50% yield production (Parven et al., 2024). In this scenario, herbicides are used to modify physiological processes in plants, acting in their metabolic pathways, and causing their death or interrupting their growth (Ghazi et al., 2023). Although, herbicides are small molecules that may not fulfill their goals and be leached, driven away, or drained, harming non-target species and humans. Besides, weeds are resisting to this agrochemical, urging new agricultural implements (Perotti et al., 2020; Yu et al., 2021). A great biotechnology potential comes from nanotechnology, bringing to materials new physical, chemical and biological characteristics (Thakur and Yadav, 2025).

Nanoparticles (structures with a nanometric size or a property) offer a higher superficial area and allow nanoherbicides to have a better interaction with plants alongside superficial charge, size, composition, solubility, and fabrication method (Jogaiah et al., 2021, Grillo et al., 2021a; Lima et al., 2022), developing focused and intelligent systems. Nanoherbicides can present vantages: delay on active degradation (Cheng et al., 2024), reduced toxicity on human cells (Dong et al., 2021a), alteration of bioactive in soil lixiviation (Kah et al., 2014) and increase herbicide activity (Oliveira et al., 2015; Pontes et al., 2021). Moreover, they have organic, inorganic and hybrid origin, highlighting the organic (or soft) nanomaterials (Forini et al. 2022) due to their biodegradability that can minimize harmful risks to non-target organisms and the ecosystem (Kusumavathi, et al., 2024).

Although some organic nanoherbicides can be fabricated through synthetic materials (Mattos et al., 2017). The natural organic nanoherbicides with lignocellulosic background have been rising in research due to their biodegradability and safe production (Chamundeeswari et al., 2019; Shrestha et al., 2021; Zhang et al., 2019; Bhattacharyya., 2020; Ur Rahim et al., 2021). Furthermore, lignocellulosic materials are obtained by agricultural waste, reinforcing the use from plant to plant, ideal scenario for a circular bioeconomy (Lima et al., 2021; Vinzant et al., 2025).

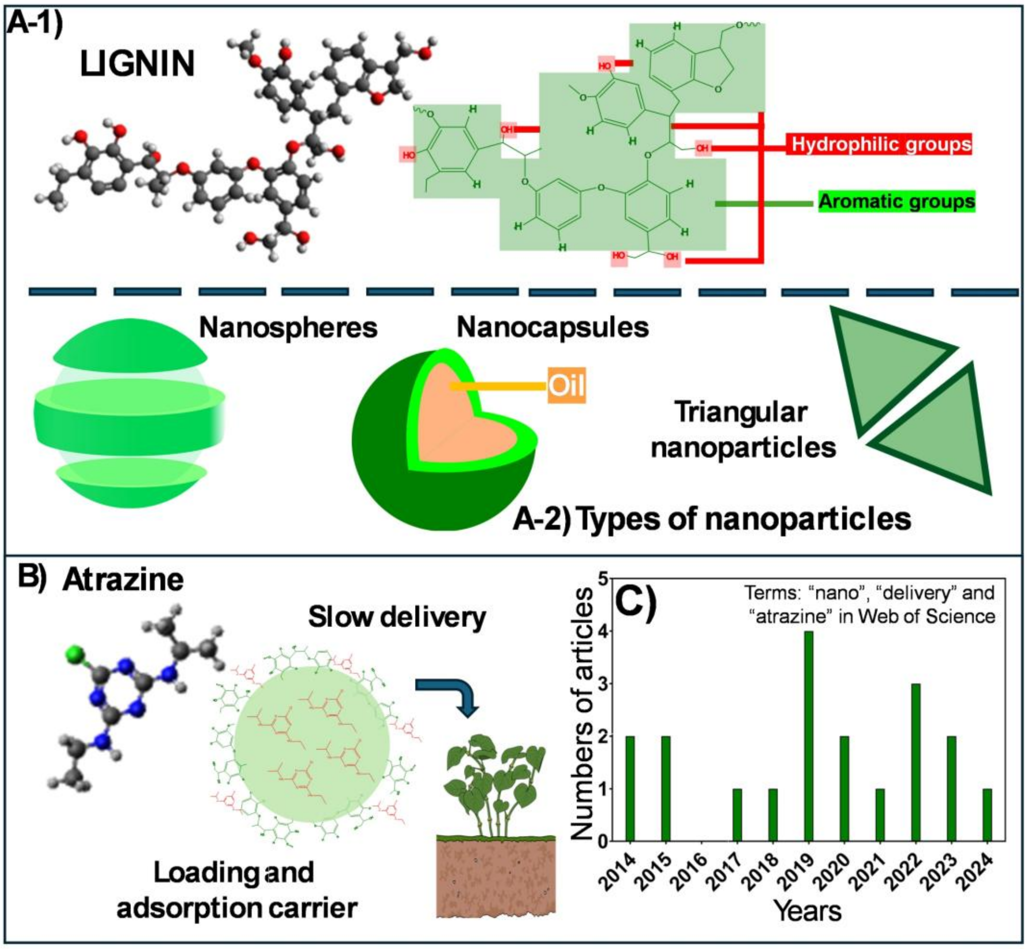

Figure 1 – (a-1) Lignin structure; (a-2) Types of lignin nanoparticles; (b) atrazine and nanospheres with a slow-release representation in plants, and (c) numbers of articles between 2014 and 2024 with the terms: "nano", "delivery", "atrazine" in the Web of Science.

Lignin is a natural organic macromolecule that came from lignocellulosic material and recently used in the fabrication of agricultural nanotools (Lima et al., 2021; Ahmad et al., 2021). Lignin is an enormous phenolic complex presented in the vegetal cell-walls, constituted by benzene units in its aromatic part and hydroxyl, carbonyls and ether functional groups in the aliphatic part (Figure 1A-1). This arrangement allows the formation of spherical, capsules and triangular shapes (Figure 1A-2), being spherical lignin nanoparticles (SLNPs) known due to their smooth surfaces (Österberg et al., 2020; Stanisz et al., 2022; Anushikha e Gaikwad, 2024; Behera et al., 2024; Dghoughi et al., 2025).

Lignin nanoparticles can be stocked without degradation for long time periods (Rodrigues et al., 2024), and can carry bioactive due to their ecological properties (biocompatibility and biodegradability) and good entrapment of active ingredients (Lima et al., 2021; Forini et al., 2022). For the nanoherbicides, lignin as matrix of nanocapsules (by nanoemulsion) and composite nanocapsules associated with polycaprolactone were presented to affect weeds (Restu et al., 2023; Restu et al., 2024; Takeshita et al., 2025). SLNPs are generally prepared by antisolvent (with water) method where the inner part is attributed to π-π benzenic rings and the surface is full of hydrogen bonds belonging to carboxylic-hydroxyl groups, in contrast to water lignin can form a nanosphere with hydrophobic core and hydrophilic shell (Trevisan et al., 2020; Santo Pereira et al., 2022).

For more efficient systems, herbicides such as atrazine (ATZ) can be carried out in possible ways: entrapping and adsorption for SLNPs and can be slow released in plants (Figure-1B) (Chandra et al., 2021; Song et al., 2024; Bryant et al., 2024). Atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) is the chloride derivative herbicide most used in grass and broadleaf weeds – 90000 tons per year. (Rostami et al., 2021). Atrazine is a persistent organic contaminant with a half-time Ambiental cycle around 2 to 57 weeks (Ganjedra et al., 2024), leading to adverse effects in non-target plants: growth inhibition, chlorophyll reduction and photosynthesis, and oxidative stress (Jiang et al., 2023a).

Atrazine has been banned in the European Union since 2003 due to its soil and water contamination and bioaccumulation that causes negative effects in non-target organisms and human health (Wu et al., 2021; Pereira et al., 2014; Queiroz et al., 2024). From the 90,000 tons of atrazine used in the field per year, around 35,000 tons are from the United States of America (Zhang et al., 2025).

In Brazil, atrazine is the fourth most sold pesticide and can be found at a concentration of 3.3 μg/L in freshwater in the southern region (Brovini et al., 2023). Currently, some nanocarriers containing atrazine have been developed with promising results in literature. From 2014 to 2024, a total of 22 articles were found when the terms “nano”, “delivery” and “atrazine” were searched in the Web of Science (Figure 1C). Therefore, understanding how nanoherbicides can affect non-target crops and weeds (target) is essential for risk assessment in agriculture (Grillo et al., 2021, Chen et al., 2024).

In this thesis, different nanocarriers for herbicide delivery consisting of lignocellulosic materials were discussed in Chapter I. Subsequently, in Chapter II it was emphasized the development (preparation and characterization) of lignin nanospheres and their ability to carry the herbicide atrazine. In addition, the effect of this nanoherbicide was evaluated on weeds of the *Tridax procumbens* (coatbuttons) in soil and Lactuca sativa (lettuce) plants (non-target) in a hydroponic system. In Chapter III, the final conclusions of the study were presented highlighting its impacts and scientific-social relevance for agribusiness.

CHAPTER III **- FINAL CONCLUSIONS, SCIENTIFIC-SOCIAL IMPACT AND RELEVANCE**

Final conclusions

Many controlled release systems for agrochemicals have been developed in recent years (Pontes et al., 2021; López-Cabeza et al., 2022). However, the design of smart nanocarriers that can be manufactured with renewable and low-cost materials is still a challenge for agricultural applications. Lignocellulosic materials (cellulose, lignin, and hemicellulose) may be ideal candidates for manufacturing green nanocarriers, given their low cost, abundance, and sustainability (Lima et al., 2021; Rodrigues et al., 2024). Lignin is a complex, three-dimensional aromatic molecule that is linked to cellulose and hemicellulose within the microstructure of the plant cell wall and is available on a large scale in agricultural waste (Lizundia et al., 2021). In recent years, lignin-based nanoparticles have been used in agriculture against fungi and insects due to their eco-friendly properties, low cost, and enhanced encapsulation properties (Ashok et al., 2018; Gigli et al., 2022).

In this thesis, the development of a new delivery system for the herbicide Atrazine (ATZ) was notified. Atrazine is a banned compound in European Union (but not in countries such as the United States and Brazil) since 2003 because its contamination and bioaccumulation affect soil and water, causing negative effects in non-target organisms and human (Wu et al., 2021; Pereira et al., 2024; Queiroz et al., 2024). For more efficient delivery systems, atrazine (ATZ) has a hydrophobic nature that can be correlated with nanoparticles with hydrophobic cores (Chandra et al., 2021; Song et al., 2024; Bryant et al., 2024). In this sense, lignin nanospheres (SLNPs) (Trevisan et al., 2020; Santo Pereira et al., 2022). – may strongly interact with atrazine. Understanding how nanoherbicides can affect non-target crops (e.g., lettuce) and more sensitive targets (weeds) is essential for risk assessment in agricultural products (Chen et al., 2024).

SLNPs have cavities in the center attributed to the π-π interaction due to benzene rings, on the other hand, the hydroxyl groups in the surface are hydrogen bonded with water (Trevisan et al., 2020; Santo Pereira et al., 2022). They have already been used to carry molecules such as resveratrol (Dai et al., 2017), but there are no reports of the use of these nanospheres in the carrying of atrazine (SLNPs_ATZ). The hypothesis of interaction between lignin and atrazine is unique with a two-way path: through adsorption and englobing (Wang et al., 2019). The nanospheres had nanometric sizes with a negative surface charge, and pH values around 6.22 and 6.51, respectively on the first day. On the seventieth, the results were 6.83 and 6.48. The encapsulation efficiency was 74.2%, suggesting an interaction between the lignin nanospheres and atrazine.

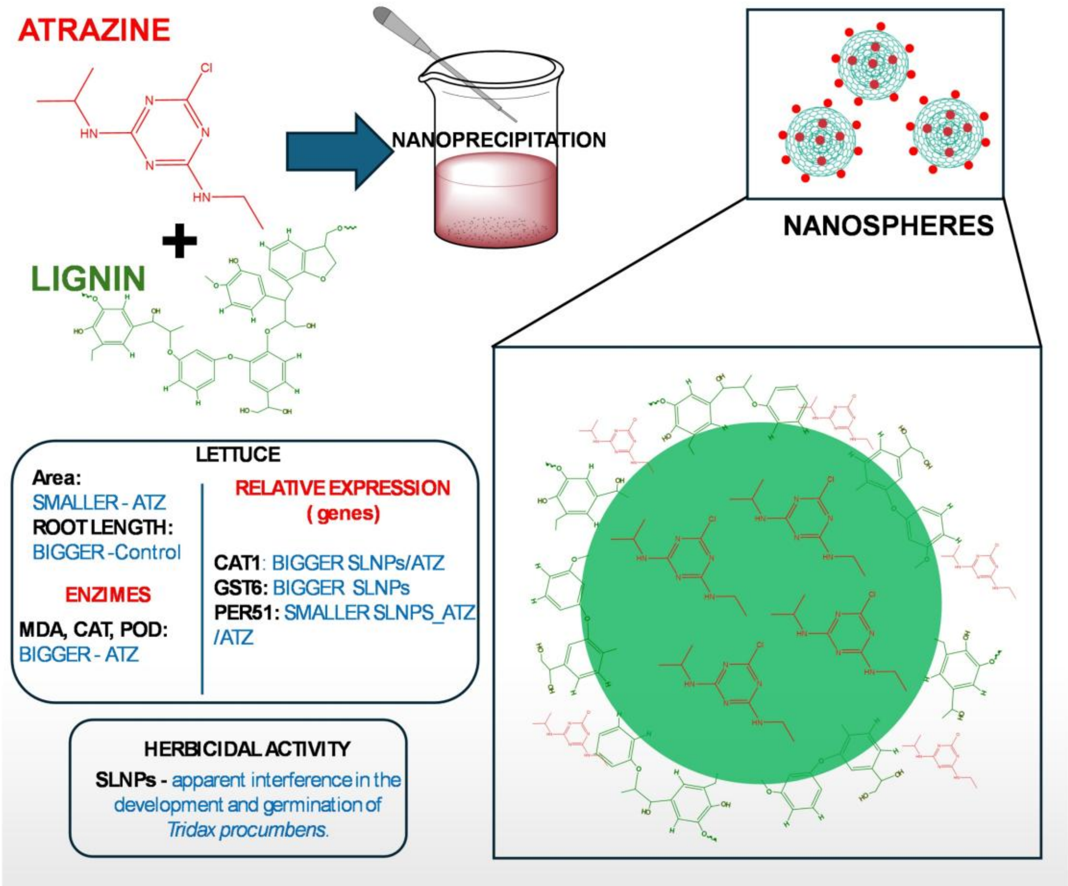

Figure 1 - Schematic representation of the lignin nanospheres containing atrazine and their interactions, and a summary of the results found in plants.

In the experiment with non-target plants (lettuce), there was a significant difference comparing root size and leaf/root area between atrazine (30 µg/L) and control, however, SLNPs and SLNPs_ATZ did not show significant changes when compared to the control. ROS species were also studied in lettuce after 28 days. Malondialdehyde (MDA) of lettuce exposed to atrazine did not reveal significant changes in the shoot, however, MDA of the roots showed significant differences comparing ATZ with all other treatments. On the other hand, Catalase (CAT) activity in the shoot of lettuce showed significant changes comparing ATZ with controls, while lettuce treated with SLNPs and SLNPs_ATZ had intermediate behavior. For guaiacol peroxidase, lettuce showed a significantly decreasing concentration in the root part (ATZ > SLNPs_ATZ > SLNPs > Control). By gene expression, the CAT1 genes were more highly expressed in lettuces treated with SLNPs and ATZ, and the GST6 genes were more highly expressed in lettuces treated with SLNPs. However, lettuces treated with SLNPs showed more physiological similarities to the control, indicating a possible tolerance of lettuces to nanoparticles. In addition, the PER51 genes were negatively expressed in plants treated with SLNPs_ATZ and ATZ, and there were no significant changes with SLNPs when compared to the control. This may have occurred because atrazine may have mutated or denatured the gene (Ramel et al., 2009). Finally, weed seeds/seedlings had possible interferences in germination/development when treated with SLNPs.

In conclusion, humanity has been trying to increase agricultural productivity with less damage to the environment. In recent years, nanotechnology has been complementing the release of active ingredients, and lignin – which comes from agricultural waste – has been indicated as a sustainable molecule in the construction of nanocarriers of agricultural bio-actives. In this context, lignin carrier nanospheres with atrazine (herbicide) were manufactured and used effectively in experiments with non-target/target plants, showing possible results in gene expression and weed control. This work will serve as a model for future studies that seek to improve sustainability and reduce the quantity of herbicides used in the field. Furthermore, in the future, lignin can be explored with other methods (encapsulation, modification, or mixture with other molecules) in the nanocarrier of herbicides (Abbas et al., 2025), aiming to increase properties and giving sustainability to new nanocarriers in agriculture.

SCIENTIFIC-SOCIAL IMPACT AND RELEVANCE

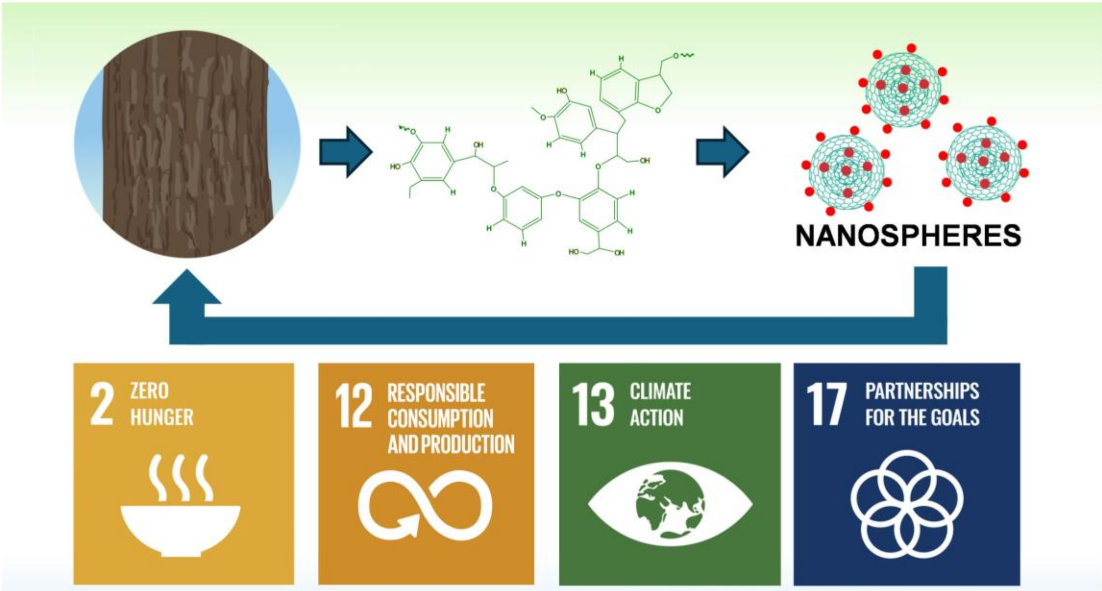

Figure 2 – Sustainable cycle scheme of lignin nanospheres and SDGs targets: number 2, 12, 13 and 17.

This technical-scientific work can be attributed to the production of new knowledge in the development of nanoparticle systems for the release of bio-actives for modern agriculture. The scientific, social, and environmental impacts in our study corroborate the Sustainable Development Goals (SDGs) established by the United Nations (UN) (Figure 2) (Cf, 2015). SDG target number 2 is reflected in our work as it advocates “End hunger, achieve food security and improve nutrition and promote sustainable agriculture” and we developed a system that promotes sustainability using a molecule derived from agricultural input and returning to the production cycle. Our system is also aligned with target number 12 “Ensure sustainable consumption and production patterns” because it is sustainable - from lignocellulosic materials.

Another highlighted goal is number 13 - take urgent action to combat climate change and its impacts – where the excessive use of herbicides causes irreparable damage to fauna, flora, and human health. This work sought to reduce the quantity of herbicides in a sustainable manner and tried to mitigate the impact of them on soil and water. In addition, goal 17 is also reflected in our research, since according to topic 17.14 "Increase policy coherence for sustainable development", this work fits this criterion. So, this work can serve as an example for future researchers, stimulating the exploration of new controlled-release nanocarriers in different agricultural contexts, contributing to the reduction of environmental impacts while increasing agricultural production.

SCIENTIFIC PRODUCTION RELATED TO THE THESIS

Published articles:

de Lima, P. H. C., Tavares, A. A., de Lima Silva, S. M., de Moura, M. R., Aouada, F. A., and Grillo, R. (2022). Recent advances on nanohybrid systems constituting clay–chitosan with organic molecules–a review. *Applied Clay Science*, *226*, 106548.

Forini, M. M., Pontes, M. S., Antunes, D. R., **de Lima, P. H**., Santos, J. S., Santiago, E. F., and Grillo, R. (2022). Nano-enabled weed management in agriculture: From strategic design to enhanced herbicidal activity. *Plant Nano Biology*, *1*, 100008.

de Lima, P. H. C., Ribeiro-Viana, R. M., Plath, A. M. S., and Grillo, R. (2024). Lignocellulosic-biomolecules conjugate systems: green-engineered complexes modified by covalent linkers. *Journal of Materials Chemistry B*.

Antunes, D. R., Forini, M. M., Coqueiro, Y. A., Pontes, M. S., **Lima, P. H.,** Cavalcante, L. A., and Grillo, R. (2024). Effect of hyaluronic acid-stabilized silver nanoparticles on lettuce (Lactuca sativa L.) seed germination. *Chemosphere*, *364*, 143080.

REFERENCES

Abbas, A., Lai, D. Y., Peng, P., and She, D. (2025). Lignin-Based Functional Materials in Agricultural Application: A Review. *Journal of Agricultural and Food Chemistry*, *73*(10), 5685-5710.

Abbati de Assis, C., Greca, L. G., Ago, M., Balakshin, M. Y., Jameel, H., Gonzalez, R., and Rojas, O. J. (2018). Techno-economic assessment, scalability, and applications of aerosol lignin micro-and nanoparticles. *ACS sustainable chemistry and engineering*, 6(9), 11853-11868.

Acharya, A., and Pal, P. K. (2020). Agriculture nanotechnology: Translating research outcome to field applications by influencing environmental sustainability. *NanoImpact*, 19, 100232.

Agathokleous, E., Feng, Z., Iavicoli, I., and Calabrese, E. J. (2020). Nano-pesticides: A great challenge for biodiversity? The need for a broader perspective. *Nano Today*, 30, 100808.

Agustin, M. B., Penttilä, P.A., Lahtinen, M., and Mikkonen, K. S. (2019). Rapid and direct preparation of lignin nanoparticles from alkaline pulping liquor by mild ultrasonication. *ACS Sustainable Chemistry and Engineering*, 7(24), 19925–19934.

Ahmad, U. M.; Ji, N.; Li, H.; Wu, Q.; Song, C.; Liu, Q.; and Lu, X. Can lignin be transformed into agrochemicals? Recent advances in the agricultural applications of lignin. (2021). Industrial Crops and Products 170, 113646.

Aijaz, N., Lan, H., Raza, T., Yaqub, M., Iqbal, R., and Pathan, M. S. (2025). Artificial Intelligence in Agriculture: Advancing Crop Productivity and Sustainability. Journal of Agriculture and Food Research, 101762.

Akpinar, I.; Drout, R. J.; Islamoglu, T.; Kato, S.; Lyu, J.; and Farha, O. K. Exploiting π–π interactions to design an efficient sorbent for atrazine removal from water. (2019). ACS Appl. Mater. Interfaces 11(6), 6097-6103.

Alscher, R. G.; Erturk, N.; Heath, L. S. (2002). Role of superoxide dismutases (SODs) in controlling oxidative stress in plants. J. Exp. Bot., 53(372), 1331-1341.

An, J.; Hu, P.; Li, F.; Wu, H.; Shen, Y.; White, J. C.; Giraldo, J. P. (2020). Emerging investigator series: molecular mechanisms of plant salinity stress tolerance improvement by seed priming with cerium oxide nanoparticles. Environ. Sci. Nano, 7(8), 2214-2228.

Antunes, D. R.; Forini, M. M.; Coqueiro, Y. A.; Pontes, M. S.; Lima, P. H.; Cavalcante, L. A.; and Grillo, R. Effect of hyaluronic acid-stabilized silver nanoparticles on lettuce (Lactuca sativa L.) seed germination. (2024). Chemosphere 364, 143080.

Anushikha; Gaikwad, K. K. Lignin as a UV blocking, antioxidant, and antimicrobial agent for food packaging applications. (2024). Biomass Conversion and Biorefinery 14(15), 16755-16767.

Ashok, R. P. B., Oinas, P., Lintinen, K., Sarwar, G., Kostiainen, M. A., and Österberg, M. (2018). Techno-economic assessment for the large-scale production of colloidal lignin particles. *Green Chemistry*, 20(21), 4911-4919.

Azevedo, R. A.; Alas, R. M.; Smith, R. J.; and Lea, P. J. Response of antioxidant enzymes to transfer from elevated carbon dioxide to air and ozone fumigation, in the leaves and roots of wild-type and a catalase-deficient mutant of barley. (1998). Physiologia Plantarum 104(2), 280-292.

Bahloul, A., Kassab, Z., El Bouchti, M., Hannache, H., Oumam, M., and El Achaby, M. (2021). Micro-and nano-structures of cellulose from eggplant plant (Solanum melongena L) agricultural residue. *Carbohydrate Polymers*, 253, 117311.

Baker, S., Volova, T., Prudnikova, S. V., Satish, S., and Prasad, N. (2017). Nanoagroparticles emerging trends and future prospect in modern agriculture system. *Environmental toxicology and pharmacology*, 53, 10-17.

Balakshin, M., and Capanema, E. (2015). On the quantification of lignin hydroxyl groups with 31P and 13C NMR spectroscopy. *Journal of Wood Chemistry and Technology*, 35(3), 220-237.

Bauli, C. R., Lima, G. F., de Souza, A. G., Ferreira, R. R., and Rosa, D. S. (2021). Eco-friendly carboxymethyl cellulose hydrogels filled with nanocellulose or nanoclays for agriculture applications as soil conditioning and nutrient carrier and their impact on cucumber growing. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 623, 126771.

Beckers, S. J., Fischer, J., and Wurm, F. R. (2021). Synthetic lignin-like and degradable nanocarriers. *Polymer Chemistry*, 12(32), 4661-4667.

Beckers, S. J., Wetherbee, L., Fischer, J., and Wurm, F. R. (2020a). Fungicide-loaded and biodegradable xylan-based nanocarriers. *Biopolymers*, 111(12), e23413.

Beckers, S., Peil, S., and Wurm, F. R. (2020b). Pesticide-Loaded Nanocarriers from Lignin Sulfonates—A Promising Tool for Sustainable Plant Protection. *ACS sustainable chemistry and engineering*, 8(50), 18468-18475.

Behera, S.; Mohapatra, S.; Behera, B. C.; and Thatoi, H. Recent updates on green synthesis of lignin nanoparticle and its potential applications in modern biotechnology. (2024). Critical Reviews in Biotechnology 44(5), 774-794.

Behtash, F.; Amini, T.; Mousavi, S. B.; Seyed Hajizadeh, H.; and Kaya, O. Efficiency of zinc in alleviating cadmium toxicity in hydroponically grown lettuce (Lactuca sativa L. cv. Ferdos). (2024). BMC Plant Biology 24(1), 648.

Belakhdar, A.; Ferkous, H.; Djellali, S.; Sahraoui, R.; Lahbib, H.; Amor, Y. B.; and Benguerba, Y. Computational and experimental studies on the efficiency of Rosmarinus officinalis polyphenols as green corrosion inhibitors for XC48 steel in acidic medium. (2020). Colloids and Surfaces A: Physicochemical and Engineering Aspects 606, 125458.

Ben Haj Fraj, S.; Chaabene, M.; Agren, S.; El Haskouri, J.; Lahcini, M.; Ben Chaâbane, R.; Baouab, M. H. V. High incorporation of magnetite nanoparticles inside tetraaza macrocyclic Schiff base cavity: spectroscopic characterization and modeling by DFT calculation. (2022). Journal of the Iranian Chemical Society 19(12), 4803-4822.

Bhattacharyya, C., Roy, R., Tribedi, P., Ghosh, A., and Ghosh, A. (2020). Biofertilizers as substitute to commercial agrochemicals. In Agrochemicals Detection, Treatment and Remediation, 263-290. *Butterworth-Heinemann*.

Bigott, Y.; Chowdhury, S. P.; Pérez, S.; Montemurro, N.; Manasfi, R.; and Schröder, P. Effect of the pharmaceuticals diclofenac and lamotrigine on stress responses and stress gene expression in lettuce (Lactuca sativa) at environmentally relevant concentrations. (2021). Journal of Hazardous Materials 403, 123881.

Brovini, E. M., Quadra, G. R., Paranaíba, J. R., Carvalho, L., de Oliveira Pereira, R., and de Aquino, S. F. (2023). Occurrence and environmental risk assessment of 22 pesticides in Brazilian freshwaters. *Aquatic Toxicology*, *260*, 106566.

Bryant, M. T.; Ren, J.; Sharma, V. K.; and Ma, X. Mutual Effects and Uptake of Organic Contaminants and Nanoplastics by Lettuce in Co-Exposure. (2024). ACS Agricultural Science and Technology 4(4), 463-470.

Carvalho, L. B.; Godoy, I. S.; Preisler, A. C.; de Freitas Proença, P. L.; Saraiva-Santos, T.; Verri, W. A.; Fraceto, L. F. Pre-emergence herbicidal efficiency and uptake of atrazine-loaded zein nanoparticles: a sustainable alternative to weed control. (2023). Environmental Science: Nano 10(6), 1629-1643.

Cf, O. D. D. S. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. *United Nations, New York*.

Chamundeeswari, M., Jeslin, J., and Verma, M. L. (2019). Nanocarriers for drug delivery applications. *Environmental Chemistry Letters*, 17(2), 849-865.

Chance, B.; and Maehly, A. C. Assay of catalases and peroxidases. (1955).

Chandra, P. N.; and Usha, K. Removal of atrazine herbicide from water by polyelectrolyte multilayer membranes. (2021). Materials Today: Proceedings 41, 622-627.

Chen, L., Zhou, H., Hao, L., Li, Z., Xu, H., Chen, H., and Zhou, X. (2020b). Dialdehyde carboxymethyl cellulose-zein conjugate as water-based nanocarrier for improving the efficacy of pesticides. *Industrial Crops and Products,* 150, 112358.

Chen, S., Ye, Y., Liao, F., Wu, S., and Zhang, K. (2024). Insight into the uptake, translocation, metabolism, dissipation and risk assessment of tolfenpyrad in romaine and edible amaranth grown in hydroponic conditions. Food Chemistry, 437, 137896.

Chen, Z., Ragauskas, A., and Wan, C. (2020a). Lignin extraction and upgrading using deep eutectic solvents. *Industrial Crops and Products*, 147, 112241.

Cheng, B.; Ding, Z.; Yue, L.; Chen, F.; Cao, X.; Li, J.; Wang, Z. (2023). Carbon dots enhanced cold tolerance of lettuce (Lactuca sativa L.): scavenging reactive oxygen species, modulating hormones and up-regulating gene expression. Environ. Sci. Nano, 10(10), 2849-2860.

Cheng, J.; Li, M.; Zhu, R. X.; Li, J. Y.; Yin, J.; and Xiao, W. A timing self-cleaning nanoherbicide: Design of triple-structure nanovectors for weed control and pesticide residues treatment. (2024). Advanced Agrochem 3(4), 298-307.

Cheng, S.; Wang, J.; Yang, J.; Wang, X.; Tang, J. An effective strategy to design high-performance wide bandgap polymer donors for organic solar cells by increasing the backbone curvature. (2023a). Dyes and Pigments 219, 111626.

Chikoye, D.; Udensi, U. E.; Lum, A. F. (2005). Evaluation of a new formulation of atrazine and metolachlor mixture for weed control in maize in Nigeria. Crop Protection, 24(11), 1016-1020.

Chowdhury, S. P.; Babin, D.; Sandmann, M.; Jacquiod, S.; Sommermann, L.; Sørensen, S. J.; and Grosch, R. (2019). Effect of long-term organic and mineral fertilization strategies on rhizosphere microbiota assemblage and performance of lettuce. Environmental Microbiology 21(7), 2426-2439.

Chowdhury, S. P.; Uhl, J.; Grosch, R.; Alquéres, S.; Pittroff, S.; Dietel, K.; and Hartmann, A. (2015). Cyclic lipopeptides of Bacillus amyloliquefaciens subsp. plantarum colonizing the lettuce rhizosphere enhance plant defense responses toward the bottom rot pathogen Rhizoctonia solani. Molecular Plant-Microbe Interactions 28(9), 984-995.

Chowdhury, M.; Samarakoon, U. C.; and Altland, J. E. Evaluation of hydroponic systems for organic lettuce production in controlled environment. (2024). Frontiers in Plant Science 15, 1401089.

Cordon, G.; Valino, I. L.; Prieto, A.; Costa, C.; Marchi, M. C.; and Diz, V. Effects of the nanoherbicide made up of atrazine-chitosan on the primary events of photosynthesis. (2022). Journal of Photochemistry and Photobiology 12, 100144.

Credou, J., and Berthelot, T. (2014). Cellulose: from biocompatible to bioactive material. *Journal of Materials Chemistry B*, 2(30), 4767-4788.

da Silva Santos, J.; da Silva Pontes, M.; Grillo, R.; Fiorucci, A. R.; de Arruda, G. J.; Santiago, E. F.; and [add if missing last author]. Physiological mechanisms and phytoremediation potential of the macrophyte Salvinia biloba towards a commercial formulation and an analytical standard of glyphosate. (2020). Chemosphere 259, 127417.

Dai, L.; Liu, R.; Hu, L. Q.; Zou, Z. F.; and Si, C. L. Lignin nanoparticle as a novel green carrier for the efficient delivery of resveratrol. (2017). ACS Sustainable Chemistry and Engineering 5(9), 8241-8249.

Darbyshire, M.; Coutts, S.; Bosilj, P.; Sklar, E.; and Parsons, S. (2024). Review of weed recognition: A global agriculture perspective. *Comput. Electron. Agric*, *227*, 109499.

Das, D., Prakash, P., Rout, P. K., and Bhaladhare, S. (2021). Synthesis and Characterization of Superabsorbent Cellulose-Based Hydrogel for Agriculture Application. *Starch‐Stärke*, 73(1-2), 1900284.

De Oliveira, F. K.; Santos, L. O.; Buffon, J. G. (2021). Mechanism of action, sources, and application of peroxidases. Food Res. Int., 143, 110266.

de Souza, V. V.; da Silva Souza, T.; de Campos, J. M. S.; de Oliveira, L. A.; Ribeiro, Y. M.; de Melo Hoyos, D. C.; and Lacerda, S. M. D. S. N. Ecogenotoxicity of environmentally relevant atrazine concentrations: a threat to aquatic bioindicators. (2023). Pestic. Biochem. Physiol. 189, 105297.

Debaeke, P.; Perronne, R.; Colbach, N.; Moreau, D.; Barre, P.; Lecouviour, F.; and Durand-Tardif, M. (2024). Non-chemical weed management: Which crop functions and traits to improve through breeding? *Crop Prot.*, 106631.

Del Buono, D.; Luzi, F.; Puglia, D. (2021). Lignin nanoparticles: A promising tool to improve maize physiological, biochemical, and chemical traits. Nanomaterials, 11(4), 846.

Dghoughi, A.; Raji, M.; Chakchak, H.; Bensalah, M. O.; Bouhfid, R.; and Qaiss, A. E. K. Synthesis of triangular lignin photonic crystal nanoparticles: Investigating solvent effects and dialysis optimization. (2025). Int. J. Biol. Macromol. 291, 139110.

Di, X.; Fu, Y.; Xu, Y.; Zheng, S.; Huang, Q.; Sun, Y. (2023). Assessment of CuO NPs on soil microbial community structure based on phospholipid fatty acid techniques and phytotoxicity of bok choy seedlings. Plant Physiol. Biochem., 197, 107657.

do Nascimento, D. M., Nunes, Y. L., de Almeida, J. S., Leitão, R. C., Feitosa, J., Dufresne, A., and Rosa, M. D. F. (2021). Development of an integrated process to produce CNFs and lignin and its potential applications for agrochemical delivery. *Cellulose*, 1-14.

Dong, J.; Liu, X.; Chen, Y.; Yang, W.; and Du, X. User-safe and efficient chitosan-gated porous carbon nanopesticides and nanoherbicides. (2021a). J. Colloid Interface Sci. 594, 20–34.

Dong, J., Chen, W., Feng, J., Liu, X., Xu, Y., Wang, C., et al. (2021b). Facile, Smart, and Degradable Metal–Organic Framework Nanopesticides Gated with FeIII-Tannic Acid Networks in Response to Seven Biological and Environmental Stimuli. *ACS Appl. Mater. Inter.* 13 (16), 19507–19520.

Doyle, J. J.; and Doyle, J. L. A rapid DNA isolation procedure for small quantities of fresh leaf tissue. (1987). Phytochem. Bull.

Eghbalinejad, M.; Hofman, J.; Kotouček, J.; Grillo, R.; Hochmanová Bílková, Z.; Reiff, N.; and Höss, S. Nano-enabled pesticides: a comprehensive toxicity assessment of tebuconazole nanoformulations with nematodes at single species and community level. (2024). Environ. Sci. Eur. 36, 51.

Ela, R. C. A., Tajiri, M., Newberry, N. K., Heiden, P. A., and Ong, R. G. (2020). Double-shell lignin nanocapsules are a stable vehicle for fungicide encapsulation and release. *ACS Sustainable Chemistry and Engineering*, 8(46), 17299-17306.

Falsini, S., Clemente, I., Papini, A., Tani, C., Schiff,S., Salvatici, M. C., Petruccelli, R., Benelli, C., Giordano, G., Gonnelli, C. and Ristori, S. (2019) When Sustainable Nanochemistry Meets Agriculture: Lignin Nanocapsules for Bioactive Compound Delivery to Plantlets. *ACS Sustainable Chemistry and Engineering*, 7 (24), 19935-19942.

Falsini, S., Tani, C., Schiff, S., Gonnelli, C., Clemente, I., Ristori, S., and Papini, A. (2020). A new method for the direct tracking of in vivo lignin nanocapsules in Eragrostis tef (Poaceae) tissues. *European journal of histochemistry: EJH*, 64(2).

Fischer, J., Beckers, S.J., Yiamsawas, D., Thines, E., Landfester, K. and Wurm, F.R. (2019). Targeted drug delivery in plants: enzyme-responsive lignin nanocarriers for the curative treatment of the worldwide grapevine trunk disease Esca. *Advanced Science*, 6, 1802315.

Forini, M. M.; Antunes, D. R.; Cavalcante, L. A.; Pontes, M. S.; Biscalchim, E. R.; Sanches, A. O.; and Grillo, R. Fabrication and characterization of a novel herbicide delivery system with magnetic collectability and its phytotoxic effect on photosystem II of aquatic macrophyte. (2020). J. Agric. Food Chem. 68(40), 11105–11113.

Forini, M. M.; Pontes, M. S.; Antunes, D. R.; de Lima, P. H.; Santos, J. S.; Santiago, E. F.; and Grillo, R. Nano-enabled weed management in agriculture: From strategic design to enhanced herbicidal activity. (2022). Plant Nano Biol. 1, 100008.

Fotovvat, M.; Najafi, F.; Khavari-Nejad, R. A.; Talei, D.; and Rejali, F. Investigating the simultaneous effect of chitosan and arbuscular mycorrhizal fungi on growth, phenolic compounds, PAL enzyme activity and lipid peroxidation in Salvia nemorosa L. (2024). Plant Physiol. Biochem. 210, 108617.

Fraceto, L. F.; Grillo, R.; de Medeiros, G. A.; Scognamiglio, V.; Rea, G.; Bartolucci, C. (2016). Nanotechnology in agriculture: which innovation potential does it have? *Front. Environ. Sci.*, *4*, 186737.

Freitas, F. M.; Cerqueira, M. A.; Gonçalves, C.; Azinheiro, S.; Garrido-Maestu, A.; Vicente, A. A.; Michelin, M. Green synthesis of lignin nano- and micro-particles: Physicochemical characterization, bioactive properties and cytotoxicity assessment. (2020). Int. J. Biol. Macromol. 163, 1798–1809.

Gajendra, G.; Pulimi, M.; Natarajan, C.; and Mukherjee, A. Occurrence, Toxicodynamics, and Mechanistic Insights for Atrazine Degradation in the Environment. (2024). Water Air Soil Pollut. 235(10), 649.

Gao, Y., Liu, Y., Qin, X., Guo, Z., Li, D., Li, C., and He, S. (2021a). Dual stimuli-responsive fungicide carrier based on hollow mesoporous silica/hydroxypropyl cellulose hybrid nanoparticles. *Journal of Hazardous Materials*, 414, 125513.

Gao, X., Fan, S., Pang, J., Rahman, M. Z., Zhu, D., Guo, S., Ma, M., and Li, Z. (2021b). Preparation of nano-xylan and its influences on the anti-fungi performance of straw fiber/HDPE composite. *Industrial Crops and Products,* 171, 113954.

Gautam, T. R.; Vasmatkar, P.; Gundloori, R. V.; Kadoo, N. Ethyl cellulose-based controlled-release atrazine nanoformulation for effective and long-term weed management in agriculture. (2025). Industrial Crops and Products 229, 120992.

Gazzurelli, C., Migliori, A., Mazzeo, P. P., Carcelli, M., Pietarinen, S., Leonardi, G., and Pelagatti, P. (2020). Making agriculture more sustainable: an environmentally friendly approach to the synthesis of lignin@ Cu pesticides. *ACS Sustainable Chemistry and Engineering*, 8(39), 14886-14895.

Ge, M.; Li, Y.; Zhu, C.; Liang, G.; SM, J. A.; Hu, G.; Gui, Y. Preparation of organic-modified magadiite–magnetic nanocomposite particles as an effective nanohybrid drug carrier material for cancer treatment and its properties of sustained release mechanism by Korsmeyer–Peppas kinetic model. (2021). J. Mater. Sci. 56(25), 14270–14286.

Ghazi, M. R., Nik Yusoff, N. R., Abdul Halim, N. S., Wahab, I. R. A., Ab Latif, N., Hasmoni, S. H., and Zakaria, Z. A. (2023). Health effects of herbicides and its current removal strategies. Bioengineered, 14(1), 2259526

Ghosh, A.; Kumar, A.; and Biswas, G (2024). Exponential population growth and global food security: challenges and alternatives. *In Bioremediation of Emerging Contaminants from Soils*, 1-20.

Gigli, M., Fellet, G., Pilotto, L., Sgarzi, M., Marchiol, L., and Crestini, C. (2022). Lignin-based nano-enabled agriculture: A mini-review. Frontiers in Plant Science, 13, 976410.

Gohar, F.; Iqbal, U. Z.; Khan, M. B.; Rehman, F.; Maryam, F. S. U.; Azmat, M.; Shahid, M. U. (2024). Impact of Nanoparticles on Plant Growth, Development and Physiological Processes: A Comprehensive Review.

Gong, Y.; Li, S.; Hu, Y.; Jin, G.; Zhou, H.; Lim, L. T.; Xiao, Q. Acidic and alkaline deep eutectic solvents pretreatment of Macadamia nutshells for production of cellulose nanofibrils and lignin nanoparticles. (2025). International Journal of Biological Macromolecules, 140251.

Grillo, R.; dos Santos, N. Z. P.; Maruyama, C. R.; Rosa, A. H.; de Lima, R.; Fraceto, L. F. Poly (ε-caprolactone) nanocapsules as carrier systems for herbicides: Physico-chemical characterization and genotoxicity evaluation. (2012). Journal of hazardous materials 231, 1-9.

Grillo, R.; Pereira, A. E.; Nishisaka, C. S.; De Lima, R.; Oehlke, K.; Greiner, R.; Fraceto, L. F. Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: an environmentally safer alternative for weed control. (2014). Journal of hazardous materials 278, 163-171.

Grillo, R., Clemente, Z., de Oliveira, J. L., Campos, E. V. R., Chalupe, V. C., Jonsson, C. M., and Fraceto, L. F. (2015). Chitosan nanoparticles loaded the herbicide paraquat: the influence of the aquatic humic substances on the colloidal stability and toxicity. *Journal of hazardous materials*, 286, 562-572.

Grillo, R.; Mattos, B. D.; Antunes, D. R.; Forini, M. M. L.; Monikh, F. A.; and Rojas, O. J. Foliage Adhesion and Interactions with Particulate Delivery Systems for Plant Nanobionics and Intelligent Agriculture. (2021a). Nano Today 37, 101078.

Grillo, R.; Fraceto, L. F.; Amorim, M. J. B.; Scott-Fordsmand, J. J.; Schoonjans, R.; and Chaudhry, Q. Ecotoxicological and Regulatory Aspects of Environmental Sustainability of Nanopesticides. (2021b). J. Hazard. Mater. 404, 124148.

Grillo, R.; Abhilash, P. C.; and Fraceto, L. F. Nanotechnology applied to bio-encapsulation of pesticides. (2016). *Journal of nanoscience and nanotechnology 16*(1), 1231-1234.

Guo, J., Tardy, B. L., Christofferson, A. J., Dai, Y., Richardson, J. J., Zhu, W., and Caruso, F. (2016). Modular assembly of superstructures from polyphenol-functionalized building blocks. *Nature nanotechnology*, *11*(12), 1105-1111.

Guo, S., He, F., Song, B., and Wu, J. (2021). Future direction of agrochemical development for plant disease in China. *Food and Energy Security*, e293.

Guo, Y.; Xu, L.; Shen, F.; Hu, J.; Huang, M.; He, J.; Tian, D. Insights into lignocellulosic waste fractionation for lignin nanospheres fabrication using acidic/alkaline deep eutectic solvents. (2022). Chemosphere 286, 131798.

Gupta, S. D.; Agarwal, A.; Pradhan, S. (2018). Phytostimulatory effect of silver nanoparticles (AgNPs) on rice seedling growth: An insight from antioxidative enzyme activities and gene expression patterns. Ecotoxicol. Environ. Saf., 161, 624–633.

Hao, L., Lin, G., Lian, J., Chen, L., Zhou, H., Chen, H., and Zhou, X. (2020). Carboxymethyl cellulose capsulated zein as pesticide nano-delivery system for improving adhesion and anti-UV properties. *Carbohydrate polymers*, 231, 115725.

Harper, A. R.; Dobson, R. C.; Morris, V. K.; Moggré, G. J. (2022). Fermentation of plant-based dairy alternatives by lactic acid bacteria. Microb. Biotechnol., 15(5), 1404–1421.

Hellal, A.; Abdelsalam, H.; Tawfik, W.; and Ibrahim, M. A. Removal of Atrazine from contaminated water by functionalized graphene quantum dots. (2024a). Opt. Quantum Electron. 56(3), 374.

Hellal, A.; Abdelsalam, H.; Tawfik, W.; Ibrahim, M. A. Assessment of doped graphene in the removal of atrazine from water. (2024b). Sci. Rep. 14(1), 21994.

Hennig, T. B.; Bandeira, F. O.; Puerari, R. C.; Fraceto, L. F.; Matias, W. G. A systematic review of the toxic effects of a nanopesticide on non-target organisms: Estimation of protective concentrations using a species sensitivity distribution (SSD) approach–The case of atrazine. (2023). Sci. Total Environ. 871, 162094.

Hoffmann, G.; Chermette, H.; Morell, C. Revisiting nucleophilicity: an index for chemical reactivity from a CDFT approach. (2024). J. Mol. Model. 30(7), 232.

Houston, R. W.; Elder, T. J.; Abdoulmoumine, N. H. Investigation into the pyrolysis bond dissociation enthalpies (BDEs) of a model lignin oligomer using density functional theory (DFT). (2022). Energy Fuels 36(3), 1565–1573.

Jiang, Y., Chen, Y., Tian, D., Shen, F., Wan, X., Xu, L., and Shen, F. (2020). Fabrication and characterization of lignin–xylan hybrid nanospheres as pesticide carriers with enzyme-mediated release property. *Soft Matter*, 16(39), 9083-9093.

Jiang, D.; Jiang, Z.; Liu, S.; Hu, Y.; Deng, S.; Wang, J.; Zhang, Y. Inhibition mechanism of atrazine on soybean growth insight from the plant nitrogen fixation and rhizobia diversity inhabiting in nodules and rhizosphere soil. (2024). Appl. Soil Ecol. 195, 105236.

Jiang, Z.; Shao, Q.; Chu, Y.; An, N.; Cao, B.; Ren, Z.; and Zhang, Y. Mitigation of atrazine-induced oxidative stress on soybean seedlings after co-inoculation with atrazine-degrading bacterium Arthrobacter sp. DNS10 and inorganic phosphorus-solubilizing bacterium Enterobacter sp. P1. (2023a). Environ. Sci. Pollut. Res. 30(11), 30048–30061.

Jiang, D.; Li, Y.; Wang, J.; Lv, X.; Jiang, Z.; Cao, B.; Zhang, Y. Exogenous application of Bradyrhizobium japonicum AC20 enhances soybean tolerance to atrazine via regulating rhizosphere soil microbial community and amino acid, carbohydrate metabolism related genes expression. (2023b). Plant Physiol. Biochem. 196, 472–483.

Jin, Y.; Yuan, X.; Lu, Y.; Teng, G.; Zhou, C.; Wang, Y.; and Zhang, J. A Self-Reportable Fluorescence Lighting-up Nanoherbicide with Minimized Off-Target Hazards. (2025). Adv. Agrochem.

Jogaiah, S., Paidi, M. K., Venugopal, K., Geetha, N., Mujtaba, M., Udikeri, S. S., and Govarthanan, M. (2021). Phytotoxicological effects of engineered nanoparticles: An emerging nanotoxicology. *Science of the Total Environment*, 149809.

Jomova, K.; Raptova, R.; Alomar, S. Y.; Alwasel, S. H.; Nepovimova, E.; Kuca, K.; Valko, M. (2023). Reactive oxygen species, toxicity, oxidative stress, and antioxidants: Chronic diseases and aging. Arch. Toxicol., 97(10), 2499–2574.

Kamble, S.; Agrawal, S.; Cherumukkil, S.; Sharma, V.; Jasra, R. V.; Munshi, P. Revisiting zeta potential, the key feature of interfacial phenomena, with applications and recent advancements. (2022). ChemistrySelect 7(1), e202103084.

Kaya, M., and Tabak, A. (2020). Recycling of an agricultural bio-waste as a novel cellulose aerogel: A green chemistry study. *Journal of Polymers and the Environment*, 28(1), 323-330.

Kaziem, A. E., Yang, L., Lin, Y., Kazem, A. E., Xu, H., and Zhang, Z. X. (2021). Pathogenic Invasion-Responsive Carrier Based on Mesoporous Silica/β-Glucan Nanoparticles for Smart Delivery of Fungicides. *ACS Sustainable Chemistry and Engineering*, 9(27), 9126-9138.

Kaziem, A. E., Yang, L., Lin, Y., Song, Z., Xu, H., and Zhang, Z. (2022). Efficiency of mesoporous silica/carboxymethyl β-glucan as a fungicide nano-delivery system for improving chlorothalonil bioactivity and reduce biotoxicity. *Chemosphere*, 287, 131902.

Kolahi, M.; Kazemi, E. M.; Yazdi, M.; Goldson-Barnaby, A. (2020). Oxidative stress induced by cadmium in lettuce (Lactuca sativa Linn.): Oxidative stress indicators and prediction of their genes. Plant Physiol. Biochem., 146, 71–89.

Kumar, S., Kumar, D., and Dilbaghi, N. (2017). Preparation, characterization, and bio-efficacy evaluation of controlled release carbendazim-loaded polymeric nanoparticles. *Environmental Science and Pollution Research*, 24(1), 926-937.

Kusumavathi, K.; Rautray, S. K.; Sarkar, S.; Dash, S.; Sahoo, T. R.; Swain, S. K.; and Sethi, D. Nano-herbicides a sustainable strategy for weed control. (2024). Plant Nano Biol. 100132.

Lee, J. H.; Kim, K.; Jin, X.; Kim, T. M.; Choi, I. G.; Choi, J. W. Formation of pure nanoparticles with solvent-fractionated lignin polymers and evaluation of their biocompatibility. (2021). Int. J. Biol. Macromol. 183, 660–667.

Lei, C.; and Engeseth, N. J. Comparison of growth characteristics, functional qualities, and texture of hydroponically grown and soil-grown lettuce. (2021). LWT 150, 111931.

Lescano, M. R.; Macagno, J.; Berli, C. L. Model-Based Analysis of Lactuca sativa Root Growth under the Action of Herbicides in Milli-Channel Arrays with In Situ Imaging. (2023). J. Agric. Food Chem. 71(36), 13255–13262.

Li, T., Lü, S., Yan, J., Bai, X., Gao, C., and Liu, M. (2019). An Environment-Friendly Fertilizer Prepared by Layer-by-Layer Self-Assembly for pH-Responsive Nutrient Release. *ACS applied materials and interfaces*, 11(11), 10941-10950.

Li, P., Huang, Y., Fu, C., Jiang, S. X., Peng, W., Jia, Y., and Xu, Z. P. (2021a). Eco-friendly biomolecule-nanomaterial hybrids as next-generation agrochemicals for topical delivery. *EcoMat*.

Li, T., Lü, S., Wang, Z., Huang, M., Yan, J., and Liu, M. (2021b). Lignin-based nanoparticles for recovery and separation of phosphate and reused as renewable magnetic fertilizers. *Science of The Total Environment*, 765, 142745.

Li, Y.; Lin, X.; Xu, G.; Yan, Q.; and Yu, Y. Toxic effects and mechanisms of engineered nanoparticles and nanoplastics on lettuce (Lactuca sativa L.). (2024). Sci. Total Environ. 908, 168421.

Lima, P. H. C. D.; Antunes, D. R.; Forini, M. M. D. L.; Pontes, M. D. S.; Mattos, B. D.; and Grillo, R. Recent advances on lignocellulosic-based nanopesticides for agricultural applications. (2021). Front. Nanotechnol. 3, 809329.

Liu, Y.; Jia, L.; Xiao, Y.; Wang, H.; Luo, X.; Wang, S.; Yin, Q. Solubility Measurement and Thermodynamic Properties of Atrazine in 13 Pure Solvents from 283.15 to 323.15 K. (2024). J. Chem. Eng. Data 70(1), 607–618.

Liu, M.; Xiang, B.; Li, H.; He, X.; Li, H.; Du, K.; Li, X. A sustainable Poly (deep eutectic solvents) based molecular imprinting strategy with experimental and theoretical elucidation: Application for removal of atrazine in agricultural wastewater. (2025). Sep. Purif. Technol. 353, 128637.

Livak, K. J.; and Schmittgen, T. D. Analysis of relative gene expression data using real-time quantitative PCR and the 2−ΔΔCT method. (2001). Methods 25(4), 402–408.

Lizundia, E., Sipponen, M. H., Greca, L. G., Balakshin, M., Tardy, B. L., and Rojas, O. J. and Puglia, D. (2021). Multifunctional lignin-based nanocomposites and nanohybrids. *Green Chemistry*, 23, 6698-6760.

López-Cabeza, R., Kah, M., Grillo, R., Koutný, M., Salač, J., Bílková, Z., and Hofman, J. (2022). Tebuconazole and terbuthylazine encapsulated in nanocarriers: preparation, characterization and release kinetics. Environmental Science: Nano, 9(4), 1427-1438.

Lourencon, T. V., Greca, L. G., Tarasov, D., Borrega, M., Tamminen, T., Rojas, O. J., and Balakshin, M. Y. (2019). Lignin-first integrated hydrothermal treatment (HTT) and synthesis of low-cost biorefinery particles. *ACS Sustainable Chemistry and Engineering*, 8(2), 1230-1239.

Lu, X.; Zhang, Y.; Chen, J.; Zhang, D.; Dong, C.; Zhiqiang, P.; Xia, T. Preparation of tailored lignin nanospheres with specific size and tunable structure by self-assembly of lignin from corn straw. (2021). Ind. Crops Prod. 172, 113993.

Ma, M., Dai, L., Xu, J., Liu, Z., and Ni, Y. (2020). A simple and effective approach to fabricate lignin nanoparticles with tunable sizes based on lignin fractionation. *Green Chemistry*, 22, 2011-2017.

Ma, Y.; Remón, J.; Luo, L.; Ding, W.; Jiang, Z.; and Shi, B. (2025).Natural-Based UV-Shielding Additives to Protect Photosensitive Pesticides: Production of Nanoparticles from the Co-Self-Assembly of Lignin and Tannin. Nano Today 60, 102550.

Machado, T. O., Beckers, S. J., Fischer, J., Muller, B., Sayer, C., Araújo, P.H.H., (2020) Landfester, K. and Wurm, R. F. Bio-based lignin nanocarriers loaded with fungicides as a versatile platform for drug delivery in plants. *Biomacromolecules*, 21, 2755−2763.

Machado, T. O., Beckers, S. J., Fischer, J., Sayer, C., de Araújo, P. H. H., Landfester, K., and Wurm, F. R. (2021). Cellulose nanocarriers via miniemulsion allow Pathogen-Specific agrochemical delivery. *Journal of colloid and interface science*, 601, 678-688.

Majid, M.; Khan, J. N.; Shah, Q. M. A.; Masoodi, K. Z.; Afroza, B.; and Parvaze, S. (2021). Evaluation of Hydroponic Systems for the Cultivation of Lettuce (Lactuca sativa L.; var. Longifolia) and Comparison with Protected Soil-Based Cultivation. Agric. Water Manag. 245, 106572.

Mattos, B. D., and Magalhães, W. L. (2016). Biogenic nanosilica blended by nanofibrillated cellulose as support for slow-release of tebuconazole. *Journal of Nanoparticle Research*, 18(9), 1-10.

Mattos, B. D., Greca, L. G., Tardy, B. L., Magalhães, W. L., and Rojas, O. J. (2018). Green formation of robust supraparticles for cargo protection and hazards control in natural environments. *Small*, 14(29), 1801256.

Mattos, B. D., Tardy, B. L., Magalhães, W. L., and Rojas, O. J. (2017). Controlled release for crop and wood protection: Recent progress toward sustainable and safe nanostructured biocidal systems. *Journal of Controlled Release,* 262, 139-150.

Mirza, L. A.; Salih, R. O.; Abdullah, N. R. Calcite nano-structure as a novel drug carrier for 5-Fluorouracil chemotherapy agent: A computational study using DFT and AIMD. (2025). Computational and Theoretical Chemistry 1248, 115181.

Moreno, A.; Sipponen, M. H. Overcoming Challenges of Lignin Nanoparticles: Expanding Opportunities for Scalable and Multifunctional Nanomaterials. (2024). Acc. Chem. Res. 57(14), 1918–1930.

Munhoz-Garcia, G. V.; Takeshita, V.; de Oliveira, J. L.; Dalla Vecchia, B.; Nalin, D.; Pinácio, C. D. W.; Fraceto, L. F. (2025). Nanobased Natural Polymers as a Carrier System for Glyphosate: An Interesting Approach Aimed at Sustainable Agriculture. J. Agric. Food Chem.

Naidu, D. S., Hlangothi, S. P., and John, M. J. (2018). Bio-based products from xylan: A review. *Carbohydrate polymers*, 179, 28-41.

Neto, F. A. N.; de Freitas Souza, M.; Blat, N. R.; da Silva, F. D.; Fernandes, B. C. C.; das Chagas, P. S. F.; Silva, D. V. (2024). Sensitivity and Antioxidant Response of Forest Species Seedlings to Atrazine under Simulated Conditions of Subsurface Water Contamination. Chemosphere, 360, 142411.

Ng, S. W.; Rosli, N. S. M.; Razali, R. B. R.; Abdullah, R.; and Yaacob, J. S. From Waste to Wealth: Significant Potential of Oil Palm Kernel-Derived Biochar as Alternative Substrate for Production of Red Lettuce (Lactuca sativa L.) with High

Bioactive Metabolites Content in NFT Hydroponic System. (2023). Sustain. Chem. Pharm. 34, 101167.

Niu, N. N.; Zhao, W. J.; Xiao, B. L.; Liang, Y. C.; Meng, X.; Song, X. Y.; Moosavi-Movahedi, A. A. (2021). Quench Treatment Cytochrome c: Transformation from a Classical Redox Protein to a Peroxidase Like Enzyme. J. Iran. Chem. Soc., 1–11.

Okolie, J. A., Nanda, S., Dalai, A. K., and Kozinski, J. A. (2021). Chemistry and specialty industrial applications of lignocellulosic biomass. *Waste and Biomass Valorization*, 12(5), 2145-2169.

Oliveira, H. C.; Stolf-Moreira, R.; Martinez, C. B. R.; Grillo, R.; de Jesus, M. B.; and Fraceto, L. F. Nanoencapsulation Enhances the Post-Emergence Herbicidal Activity of Atrazine against Mustard Plants. (2015). PLoS One 10(7), e0132971.

Österberg, M.; Sipponen, M. H.; Mattos, B. D.; and Rojas, O. J. Spherical Lignin Particles: A Review on Their Sustainability and Applications. (2020). Green Chem. 22(9), 2712–2733.

Papadopoulos, A. N., Bikiaris, D. N., Mitropoulos, A. C., and Kyzas, G. Z. (2019). Nanomaterials and chemical modifications for enhanced key wood properties: A review. *Nanomaterials*, 9(4), 607.

Parkinson, S. J.; Tungsirisurp, S.; Joshi, C.; Richmond, B. L.; Gifford, M. L.; Sikder, A.; Napier, R. M. Polymer Nanoparticles Pass the Plant Interface. (2022). Nat. Commun. 13(1), 7385.

Parven, A., Meftaul, I. M., Venkateswarlu, K., and Megharaj, M. (2024). Herbicides in modern sustainable agriculture: Environmental fate, ecological implications, and human health concerns. International Journal of Environmental Science and Technology, 1-22.

Pearson, R. G. The principle of maximum hardness. (1993). Accounts of Chemical Research 26(5), 250-255.

Peil, S., Beckers, S. J., Fischer, J., and Wurm, F. R. (2020). Biodegradable, lignin-based encapsulation enables delivery of Trichoderma reesei with programmed enzymatic release against grapevine trunk diseases. *Materials Today Bio*, 7, 100061.

Peng, R., Yang, D., Qiu, X., Qin, Y., and Zhou, M. (2020). Preparation of self-dispersed lignin-based drug-loaded material and its application in avermectin nano-formulation. *International journal of biological macromolecules*, 151, 421-427.

Peng, Q.; Ye, L.; Wen, N.; Chen, H.; Zhu, Y.; Niu, H.; Huang, Y. Nitrogen Vacancy-Modified g-C3N4 Nanosheets Controlled by Deep Eutectic Solvents for Highly Efficient Photocatalytic Atrazine Degradation: Non-Radical Dominated Holes Oxidation. (2025). Sep. Purif. Technol. 354, 128879.

Pereira, A. E.; Grillo, R.; Mello, N. F.; Rosa, A. H.; and Fraceto, L. F. Application of Poly(ε-caprolactone) Nanoparticles Containing Atrazine Herbicide as an Alternative Technique to Control Weeds and Reduce Damage to the Environment. (2014). J. Hazard. Mater. 268, 207–215.

Pérez, D. J.; Doucette, W. J.; and Moore, M. T. Atrazine Uptake, Translocation, Bioaccumulation and Biodegradation in Cattail (Typha latifolia) as a Function of Exposure Time. (2022). Chemosphere 287, 132104.

Perotti, V. E.; Larran, A. S.; Palmieri, V. E.; Martinatto, A. K.; and Permingeat, H. R. (2020). Herbicide Resistant Weeds: A Call to Integrate Conventional Agricultural Practices, Molecular Biology Knowledge and New Technologies. *Plant Sci. 290*, 110255.

Pontes, M. S., Antunes, D. R., Oliveira, I. P., Forini, M. M., Santos, J. S., Arruda, G. J., and Grillo, R. (2021). Chitosan/tripolyphosphate nanoformulation carrying paraquat: insights on its enhanced herbicidal activity. *Environmental Science: Nano*, 8(5), 1336-1351.

Preisler, A. C.; Carvalho, L. B.; Saraiva-Santos, T.; Verri Jr, W. A.; Mayer, J. L. S.; Fraceto, L. F.; and Oliveira, H. C. (2022). Interaction of Nanoatrazine and Target Organism: Evaluation of Fate and Photosystem II Inhibition in Hydroponically Grown Mustard (Brassica juncea) Plants.. J. Agric. Food Chem. 70(25), 7644–7652.

Qi, Y.; Li, J.; Fu, G.; Zhao, C.; Guan, X.; Yan, B.; and Ren, M. (2018). Effects of Sublethal Herbicides on Offspring Germination and Seedling Growth: Redroot Pigweed (Amaranthus retroflexus) vs. Velvetleaf (Abutilon theophrasti). Sci. Total Environ., 645, 543–549.

Queiroz, A. M.; Pontes, M. S.; Scherer, M. D.; Graciano, D. E.; Caires, A. R.; and Oliveira, S. L. Root Length as a Bioindicator of Pesticide Concentration in Irrigation Water. (2024). Environ. Sci. Pollut. Res., 1–8.

Ramel, F.; Sulmon, C.; Bogard, M.; Couée, I.; and Gouesbet, G. (2009). Differential Patterns of Reactive Oxygen Species and Antioxidative Mechanisms during Atrazine Injury and Sucrose-Induced Tolerance in Arabidopsis thaliana Plantlets. BMC Plant Biol., 9, 1–18.

Rashidipour, M., Maleki, A., Kordi, S., Birjandi, M., Pajouhi, N., Mohammadi, E., and Davari, B. (2019). Pectin/chitosan/tripolyphosphate nanoparticles: efficient carriers for reducing soil sorption, cytotoxicity, and mutagenicity of paraquat and enhancing its herbicide activity. *Journal of agricultural and food chemistry*, 67(20), 5736-5745.

Rashidipour, M., Rasoulian, B., Maleki, A., Davari, B., Pajouhi, N., and Mohammadi, E. (2021). Pectin/chitosan/tripolyphosphate encapsulation protects the rat lung from fibrosis and apoptosis induced by paraquat inhalation. *Pesticide Biochemistry and Physiology*, 178, 104919.

Rawashdeh, R. Y.; Harb, A. M.; and AlHasan, A. M. Biological Interaction Levels of Zinc Oxide Nanoparticles; Lettuce Seeds as Case Study. (2020). Heliyon 6(5).

Restu, W. K.; Aryana, N.; Septiyanti, M.; Triwulandari, E.; Sampora, Y.; Devy, Y. A.; and Ogino, C. Development of a Lignin-Based Carrier-Citronella Oil Nanoemulsion and Its Utilization as an Herbicide against Specific Weed Species. (2024). Chem. Biodiversity 21(9), e202400861.

Restu, W. K.; Septiyanti, M.; Triwulandari, E.; Aryana, N.; Sampora, Y.; Devy, Y. A.; and Ogino, C. The Preparation of Nanoemulsion Formulation from Pelargonic Acid in Lignin Carrier and Its Application to Weeds. (2023). J. Inst. Eng. (India): Ser. E 104(2), 297–303.

Ribeiro, C.; Stitt, M.; Hotta, C. T. How Stress Affects Your Budget—Stress Impacts on Starch Metabolism. (2022). Front. Plant Sci. 13, 774060.

Ritger, P. L.; and Peppas, N. A. A Simple Equation for Description of Solute Release I. Fickian and Non-Fickian Release from Non-Swellable Devices in the Form of Slabs, Spheres, Cylinders or Discs. (1987). J. Control. Release 5(1), 23–36.

Rodrigues, J. S.; Takeshita, V.; Campos, E. V.; de Freitas, A. S.; de Lima, V. H.; and Fraceto, L. F. Lignocellulosic Biomass in Nanopesticides: A Path toward Sustainable Agriculture. (2024). ACS Sustainable Chem. Eng. 12(27), 10045–10067.

Rop, K., Mbui, D., Karuku, G. N., Michira, I., and Njomo, N. (2020). Characterization of water hyacinth cellulose-g-poly (ammonium acrylate-co-acrylic acid)/nano-hydroxyapatite polymer hydrogel composite for potential agricultural application. *Results in Chemistry*, 2, 100020.

Rostami, S., Jafari, S., Moeini, Z., Jaskulak, M., Keshtgar, L., Badeenezhad, A. and Dehghani, M. (2021). Current methods and technologies for degradation of atrazine in contaminated soil and water: A review. Environmental Technology and Innovation, 24, 102019.

Saleem, H., and Zaidi, S. J. (2020). Recent developments in the application of nanomaterials in agroecosystems. *Nanomaterials*, 10(12), 2411.

Salinas, F.; Astete, C. E.; Waldvogel, J. H.; Navarro, S.; White, J. C.; Elmer, W.; Sabliov, C. M. (2021). Effects of Engineered Lignin-Graft-PLGA and Zein-Based Nanoparticles on Soybean Health. NanoImpact, 23, 100329.

Santo Pereira, A. D. E.; de Oliveira, J. L.; Savassa, S. M.; Rogerio, C. B.; de Medeiros, G. A.; and Fraceto, L. F. Lignin Nanoparticles: New Insights for a Sustainable Agriculture. (2022). J. Cleaner Prod. 345, 131145.

Sathishkumar, P.; Li, Z.; Govindan, R.; Jayakumar, R.; Wang, C.; Gu, F. L. Zinc Oxide-Quercetin Nanocomposite as a Smart Nano-Drug Delivery System: Molecular-Level Interaction Studies. (2021). Appl. Surf. Sci. 536, 147741.

Schiavi, D., Balbi, R., Giovagnoli, S., Camaioni, E., Botticella, E., Sestili, F., and Balestra, G. M. (2021). A Green Nanostructured Pesticide to Control Tomato Bacterial Speck Disease. *Nanomaterials*, 11(7), 1852.

Shahi, N., Wang, P., Adhikari, S., Min, B., and Rangari, V. K. (2021). Biopolymers Fractionation and Synthesis of Nanocellulose/Silica Nanoparticles from Agricultural Byproducts. ACS Sustainable *Chemistry and Engineering*, 9(18), 6284-6295.

Shahid, M.; Shafi, Z.; Ilyas, T.; Singh, U. B.; Pichtel, J. Crosstalk between Phytohormones and Pesticides: Insights into Unravelling the Crucial Roles of Plant Growth Regulators in Improving Crop Resilience to Pesticide Stress. (2024). Sci. Hortic. 338, 113663.

Shakiba, S.; Astete, C. E.; Paudel, S.; Sabliov, C. M.; Rodrigues, D. F.; Louie, S. M. Emerging investigator series: polymeric nanocarriers for agricultural applications: synthesis, characterization, and environmental and biological interactions. (2020). Environ. Sci.: Nano 7(1), 37–67.

Sharif, S. N. M., Hashim, N., Isa, I. M., Bakar, S. A., Saidin, M. I., Ahmad, M. S., and Zainul, R. (2021). Polymeric Nanocomposite-Based Herbicide of Carboxymethyl Cellulose Coated-Zinc/Aluminium Layered Double Hydroxide-Quinclorac: A Controlled Release Purpose for Agrochemicals. *Journal of Polymers and the Environment*, 29(6), 1817-1834.

Sharifan, H.; Ma, X.; Moore, J. M.; Habib, M. R.; and Evans, C. Zinc Oxide Nanoparticles Alleviated the Bioavailability of Cadmium and Lead and Changed the Uptake of Iron in Hydroponically Grown Lettuce (Lactuca sativa L. var. Longifolia). (2019). ACS Sustainable Chem. Eng. 7(19), 16401.

Sharma, R., Bajpai, J., Bajpai, A. K., Acharya, S., Kumar, B., and Singh, R. K. (2017). Assessment of water retention performance of pectin-based nanocarriers for controlled irrigation in agriculture. *Agricultural Research*, 6(2), 139-149.

Sharma, S.; Kachhia, P.; Shukla, V.; Patel, A.; Rathod, V.; Narra, M. Valorization of lignin into nanoparticles and nanogel: Characterization and application. (2022). Bioresour. Technol. Rep. 18, 101041.

Shatilov, M. V.; Razin, A. F.; and Ivanova, M. I. Analysis of the world lettuce market. In IOP Conf. Ser.: Earth Environ. Sci.; IOP Publishing, 2019; Vol. 395, No. 1, p 012053.

Shatkin, J. A., and Kim, B. (2015). Cellulose nanomaterials: life cycle risk assessment, and environmental health and safety roadmap. *Environmental Science: Nano*, 2(5), 477-499.

Sherard, M. M.; Dang, Q. M.; Reiff, S. C.; Simpson, J. H.; Leopold, M. C. On-site detection of neonicotinoid pesticides using functionalized gold nanoparticles and halogen bonding. (2023). ACS Appl. Nano Mater. 6(10), 8367–8381.

Shrestha, S., Kognou, A. L. M., Zhang, J., and Qin, W. (2021). Different facets of lignocellulosic biomass including pectin and its perspectives. Waste and Biomass Valorization, 12(9), 4805-4823.

Shu, F.; Jiang, B.; Yuan, Y.; Li, M.; Wu, W.; Jin, Y.; and Xiao, H. Biological activities and emerging roles of lignin and lignin-based products—A review. (2021). Biomacromolecules 22(12), 4905–4918.

Sikder, A., Pearce, A. K., Parkinson, S. J., Napier, R., and O'Reilly, R. K. (2021). Recent trends in advanced polymer materials in agriculture related applications. *ACS Applied Polymer Materials*, 3(3), 1203-1217.

Simoni, S.; Castellacci, M.; Usai, G.; Rogo, U.; Mascagni, F.; Giordani, T.; Vangelisti, A. (2024). Genome-Wide Characterization of Class III Peroxidases and Their Expression Profile during Mycorrhizal Symbiosis and Phosphorus Deprivation in Lettuce (Lactuca sativa L.). Horticulturae, 10(11), 1170.

Singh, H., Sharma, A., Bhardwaj, S. K., Arya, S. K., Bhardwaj, N., and Khatri, M. (2021). Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environmental Science: Processes and Impacts*, 23(2), 213-239.

Sipponen, M. H., Rojas, O. J., Pihlajaniemi, V., Lintinen, K., and Österberg, M. (2017). Calcium chelation of lignin from pulping spent liquor for water-resistant slow-release urea fertilizer systems. *ACS Sustainable Chemistry and Engineering*, *5*(1), 1054-1061.

Siqueira, J. G. W., Rodrigues, C., de Souza Vandenberghe, L. P., Woiciechowski, A. L., and Soccol, C. R. (2020). Current advances in on-site cellulase production and application on lignocellulosic biomass conversion to biofuels: a review. *Biomass and Bioenergy*, 132, 105419.

Sobiecka, E.; Mroczkowska, M.; Olejnik, T. P. (2022). The Enzymatic Antioxidants Activities Changes in Water Plants Tissues Exposed to Chlorpyrifos Stress. Antioxidants, 11(11), 2104.

Song, L.; Cheng, H.; Liu, C.; Ji, R.; Yao, S.; Cao, H.; and Song, Y. Oyster Shell Facilitates the Green Production of Nitrogen-Doped Porous Biochar from Macroalgae: A Case Study for Removing Atrazine from Water. (2024). Biochar 6(1), 76.

Sousa, G. F.; Gomes, D. G.; Campos, E. V.; Oliveira, J. L.; Fraceto, L. F.; Stolf-Moreira, R.; Oliveira, H. C. (2018). Post-Emergence Herbicidal Activity of Nanoatrazine against Susceptible Weeds. *Front. Environ. Sci*, *6*, 12.

Sousa, B. T.; Carvalho, L. B.; Preisler, A. C.; Saraiva-Santos, T.; Oliveira, J. L.; Verri Jr, W. A.; and Oliveira, H. Chitosan Coating as a Strategy to Increase Postemergent Herbicidal Efficiency and Alter the Interaction of Nanoatrazine with Bidens pilosa Plants. (2024). ACS Appl. Mater. Interfaces.

Stanisz, M.; Collins, M. N.; and Jesionowski, T. Recent progress in biomedical and biotechnological applications of lignin-based spherical nano- and microstructures: a comprehensive review. (2022). Mater. Today Chem. 26, 101198.

Stloukal, P.; Kucharczyk, P.; Sedlarik, V.; Bazant, P.; Koutny, M. Low molecular weight poly(lactic acid) microparticles for controlled release of the herbicide metazachlor: preparation, morphology, and release kinetics. (2012). J. Agric. Food Chem. 60(16), 4111–4119.

Su, S., Chen, L., Hao, L., Chen, H., Zhou, X., and Zhou, H. (2021a). Fluorinated sodium carboxymethyl cellulose nanoparticles as carrier for improving adhesion and sustaining release of AVM. *Journal of Macromolecular Science*, Part A, 58(4), 219-231.

Su, S., Chen, L., Hao, L., Chen, H., Zhou, X., and Zhou, H. (2021c). Preparation of p-amino salicylic acid-modified polysuccinimide as water-based nanocarriers for enhancing pesticide stability and insecticidal activity. *Colloids and Surfaces B: Biointerfaces*, 207, 111990.

Su, Y., Chen, L., Yang, F., and Cheung, P. C. (2021b). Beta-d-glucan-based drug delivery system and its potential application in targeting tumor associated macrophages. *Carbohydrate polymers*, 253, 117258.

Sun, H., Erdman III, W., Yuan, Y., Mohamed, M. A., Xie, R., Wang, Y., and Cheng, C. (2020). Crosslinked polymer nanocapsules for therapeutic, diagnostic, and theranostic applications. Wiley Interdisciplinary Reviews: *Nanomedicine and Nanobiotechnology*, 12(6), e1653.

Swapnil, P.; Meena, M.; Singh, S. K.; Dhuldhaj, U. P.; Marwal, A. (2021). Vital roles of carotenoids in plants and humans to deteriorate stress with its structure, biosynthesis, metabolic engineering and functional aspects. Curr. Plant Biol., 26, 100203.

Taban, A.; Saharkhiz, M. J.; Khorram, M. (2020). Formulation and assessment of nano-encapsulated bioherbicides based on biopolymers and essential oil. Ind. Crops Prod., 149, 112348.

Takeshita, V.; Oliveira, F. F.; Garcia, A.; Zuverza-Mena, N.; Tamez, C.; Cardoso, B. C.; and White, J. C. Delivering metribuzin from biodegradable nanocarriers: assessing herbicidal effects for soybean plant protection and weed control. (2025). Environ. Sci.: Nano.

Tardy, B. L., Mattos, B. D., Otoni, C. G., Beaumont, M., Majoinen, J., Kämäräinen, T., and Rojas, O. J. (2021). Deconstruction and Reassembly of Renewable Polymers and Biocolloids into Next Generation Structured Materials. *Chemical Reviews*.

Teo, H. L., and Wahab, R. A. (2020). Towards an eco-friendly deconstruction of agro-industrial biomass and preparation of renewable cellulose nanomaterials: A review. *International journal of biological macromolecules*.

Thakur, N., and Yadav, A. N. (2025). Nanotechnology in Agriculture: A Review on Precision Farming and Sustainable Crop Production. BioNanoScience, 15(2), 243.

Trevisan, H.; and Rezende, C. A. Pure, stable and highly antioxidant lignin nanoparticles from elephant grass. (2020). Ind. Crops Prod. 145, 112105.

Tripathi, D.; Singh, M.; Pandey-Rai, S. (2022). Crosstalk of nanoparticles and phytohormones regulate plant growth and metabolism under abiotic and biotic stress. Plant Stress, 6, 100107.

Ur Rahim, H., Qaswar, M., Uddin, M., Giannini, C., Herrera, M. L., and Rea, G. (2021). Nano-Enable Materials Promoting Sustainability and Resilience in Modern Agriculture. Nanomaterials, 11(8), 2068.

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., ur Rehman, H., and Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of the Total Environment*, 721, 137778.

Vieira, L. A.; Alves, R. D.; Menezes-Silva, P. E.; Mendonça, M. A.; Silva, M. L.; Silva, M. C.; Farnese, F. S. Water contamination with atrazine: is nitric oxide able to improve Pistia stratiotes phytoremediation capacity? (2021). Environ. Pollut. 272, 115971.

Vinzant, K., Rashid, M., Clouse, D. E., Ghosh, P., Quadir, M., Davis, V. A., and Khodakovskaya, M. V. (2025). From Plants to Plants: Plant-Derived Biological Polymers as Sustainable and Safe Nanocarriers for Direct Delivery of DNA to Plant Cells. Nano Letters.

Wang, D.; Saleh, N. B.; Byro, A.; Zepp, R.; Sahle-Demessie, E.; Luxton, T. P.; Su, C. (2022). Nano-enabled pesticides for sustainable agriculture and global food security. Nat. Nanotechnol., 17(4), 347–360.

Wang, J.; Ma, Y.; Huang, X.; Song, L.; Li, N.; Cheng, Y.; and Hai, D. Changes in physio-biochemical metabolism, phenolics and antioxidant capacity of different Chinese pea varieties during germination. (2023). Int. J. Food Sci. Technol. 58(1), 167–180.

Wang, N.; Cheng, X.; Li, N.; Wang, H.; and Chen, H. Nanocarriers and their loading strategies. (2019). Adv. Healthcare Mater. 8(6), 1801002.

Wang, Q.; Wang, H.; Chen, H.; Meng, Z.; Kong, F.; Liu, Y.; and Jiang, W. Efficient synthesis of highly hydrophobic lignin nanoparticles and their application as nano fillers for multifunctional composite membranes. (2024). Int. J. Biol. Macromol. 282, 136869.

Wang, H.; Liu, M.; Tan, S.; Li, X.; Huang, M.; Hao, X.; and Peng, F. Porous lignin nanospheres as microscopic air purifiers for antioxidant-configurable cigarette filters. (2025a). Adv. Funct. Mater. 2420731.

Wang, Y.; Chen, Y.; Wang, L.; Mo, Y.; Lin, X.; Gao, S.; Chen, M. Efficient removal of atrazine in wastewater by washed peanut shells biochar: Adsorption behavior and biodegradation. (2025b). Process Biochem.

Wang, Y.; Ma, X.; Shang, W.; Luo, H.; Wang, L.; Sun, K.; Zhang, T. (2025c). Comparative transcriptome analysis reveals differential mechanisms of soft rot resistance in lettuce grown under white and blue light. Food Energy Secur., 14(1), e70038.

Weng, Y.; Bai, X.; Kang, M.; Ji, Y.; Wang, H.; Liu, Y. (2025). Detoxification strategy of titanium oxide nanoparticles driving endogenous molecules metabolism to modulate atrazine conversion in Lactuca sativa L. Environ. Sci. Technol., 59(13), 6440–6451.

Wijaya, C. J., Ismadji, S., and Gunawan, S. (2021). A Review of Lignocellulosic-Derived Nanoparticles for Drug Delivery Applications: Lignin Nanoparticles, Xylan Nanoparticles, and Cellulose Nanocrystals. *Molecules*, 26(3), 676.

Worrall, E. A., Hamid, A., Mody, K. T., Mitter, N., and Pappu, H. R. (2018). Nanotechnology for plant disease management. *Agronomy*, 8(12), 285.

Wu, J.; Zhai, Y.; Monikh, F. A.; Arenas-Lago, D.; Grillo, R.; Vijver, M. G.; and Peijnenburg, W. J. The differences between the effects of a nanoformulation and a conventional form of atrazine to lettuce: physiological responses, defense mechanisms, and nutrient displacement. (2021). J. Agric. Food Chem. 69(42), 12527–12540.

Xie, J.; Cao, B.; and Xu, K. Uncovering the dominant role of root lignin accumulation in silicon-induced resistance to drought in tomato. (2024). Int. J. Biol. Macromol. 259, 129075.

Xing, R.; He, J.; Hao, P.; Zhou, W. Graphene oxide-supported nanoscale zero-valent iron composites for the removal of atrazine from aqueous solution. (2020). Colloids and Surfaces A: Physicochemical and Engineering Aspects 589, 124466.

Xiong, F.; Han, Y.; Wang, S.; Li, G.; Qin, T.; Chen, Y.; Chu, F. Preparation and formation mechanism of size-controlled lignin nanospheres by self-assembly. (2017). Ind. Crops Prod. 100, 146–152.

Xu, J.; Luo, X.; Wang, Y.; and Feng, Y. Evaluation of zinc oxide nanoparticles on lettuce (Lactuca sativa L.) growth and soil bacterial community. (2018). Environ. Sci. Pollut. Res. 25, 6026–6035.

Xu, L.; Wang, X.; Shi, H.; Hua, B.; Burken, J. G.; Ma, X.; and Yang, J. J. Uptake of engineered metallic nanoparticles in soil by lettuce in single and binary nanoparticle systems. (2022). ACS Sustainable Chem. Eng. 10(50), 16692–16700.

Yamaguchi, A.; Mimura, N.; Shirai, M.; and Sato, O. Bond cleavage of lignin model compounds into aromatic monomers using supported metal catalysts in supercritical water. (2017). Sci. Rep. 7(1), 46172.

Yao, T.; Feng, K.; Xie, M.; Barros, J.; Tschaplinski, T. J.; Tuskan, G. A.; and Chen, J. G. Phylogenetic occurrence of the phenylpropanoid pathway and lignin biosynthesis in plants. (2021). Front. Plant Sci. 12, 704697.

Ye, L., Han, Y., Wang, X., Lu, X., Qi, X., and Yu, H. (2021). Recent progress in furfural production from hemicellulose and its derivatives: Conversion mechanism, catalytic system, solvent selection. *Molecular Catalysis*, 515, 111899.

Yearla, S. R., and Padmasree, K. (2016). Exploitation of subabul stem lignin as a matrix in controlled release agrochemical nanoformulations: a case study with herbicide diuron. *Environmental Science and Pollution Research*, 23(18), 18085-18098.

Yiamsawas, D., Kangwansupamonkon, W., and Kiatkamjornwong, S. (2021). Lignin-based nanogels for the release of payloads in alkaline conditions. *European Polymer Journal*, 145, 110241.

Yin, J. M., Wang, H. L., Yang, Z. K., Wang, J., Wang, Z., Duan, L. S., and Tan, W. M. (2020). Engineering Lignin Nanomicroparticles for the Antiphotolysis and Controlled Release of the Plant Growth Regulator Abscisic Acid. *Journal of Agricultural and Food Chemistry*, 68(28), 7360-7368.

Yu, M., Sun, C., Xue, Y., Liu, C., Qiu, D., Cui, B., and Zeng, Z. (2019). Tannic acid-based nanopesticides coating with highly improved foliage adhesion to enhance foliar retention. *RSC advances*, *9*(46), 27096-27104. h

Yu, M.; Dong, H.; Liu, K.; Zheng, Y.; Hoffmann, M. R.; Liu, W. (2021). Porous carbon monoliths for electrochemical removal of aqueous herbicides by "one-stop" catalysis of oxygen reduction and H2O2 activation. *J. Hazard. Mater. 414*, 125592.

Zhai, Y.; Abdolahpur Monikh, F.; Wu, J.; Grillo, R.; Arenas-Lago, D.; Darbha, G. K.; Vijver, M. G.; and Peijnenburg, W. J. G. M. Interaction between a nano-formulation of atrazine and rhizosphere bacterial communities: atrazine degradation and bacterial community alterations. (2020). Environ. Sci.: Nano 7, 3372–3384.

Zhang, L., Peng, X., Zhong, L., Chua, W., Xiang, Z., and Sun, R. (2019). Lignocellulosic biomass derived functional materials: synthesis and applications in biomedical engineering. *Current medicinal chemistry*, 26(14), 2456-2474.

Zhang, S., Fu, X., Tong, Z., Liu, G., Meng, S., Yang, Y., and Li, Y. C. (2020). Lignin–Clay Nanohybrid Biocomposite-Based Double-Layer Coating Materials for Controllable-Release Fertilizer. *ACS Sustainable Chemistry and Engineering,* 8(51), 18957-18965.

Zhang, D. X., Du, J., Wang, R., Luo, J., Jing, T. F., Li, B. X., and Hou, Y. (2021a). Core/Shell Dual-Responsive Nanocarriers via Iron-Mineralized Electrostatic Self-Assembly for Precise Pesticide Delivery. *Advanced Functional Materials*, 2102027.

Zhang, J. J.; Yang, H. Metabolism and detoxification of pesticides in plants. (2021b). Sci. Total Environ. 790, 148034.

Zhang, Z.; Marin, C. B.; Lefebvre, M.; Lefebvre, C.; Terrasson, V.; Guénin, E. The preparation of stable spherical alkali lignin nanoparticles with great thermal stability and no cytotoxicity. (2022). Int. J. Biol. Macromol. 222, 1830–1839.

Zhang, Y.; Xu, J.; Li, R.; Ge, Y.; Li, Y.; Li, R. (2023). Plants' response to abiotic stress: Mechanisms and strategies. Int. J. Mol. Sci., 24(13), 10915.

Zhang, H.; Xu, W.; Li, G.; Qu, H.; Ma, C.; Noruzi, E. B.; Li, H. Controlled release system of nanopesticides based on noncovalent interactions. (2024a). ACS Agric. Sci. Technol. 4(9), 851–871.

Zhang, Y.; Li, Z.; Zhang, N.; Chai, X. (2024b). The effects of FR and UVA irradiation timing on multi-omics of purple lettuce in plant factories. Agriculture, 14(11), 2019.

Zhang, L., Xu, L., Zhang, Z., Li, J., Ren, L., Liu, Z., and Chen, Y. (2025). Influence Mechanism of Vermicompost with Different Maturity on Atrazine Catabolism and Bacterial Community. *Toxics*, *13*(1), 30.

Zhao, J.; Lu, C.; Tariq, M.; Xiao, Q.; Zhang, W.; Huang, K.; Liu, Z. (2019). The response and tolerance mechanisms of lettuce (Lactuca sativa L.) exposed to nickel in a spiked soil system. Chemosphere, 222, 399–406.

Zhao, M., Zhou, H., Hao, L., Chen, H., and Zhou, X. (2021a). A high-efficient nano pesticide-fertilizer combination fabricated by amino acid-modified cellulose based carriers. *Pest Management Science*.

Zhao, M., Zhou, H., Hao, L., Chen, H., and Zhou, X. (2021b). Natural rosin modified carboxymethyl cellulose delivery system with lowered toxicity for long-term pest control. *Carbohydrate Polymers*, 259, 117749.

Zhao, Y. W.; Wang, C. K.; Huang, X. Y.; Hu, D. G. (2021c). Anthocyanin stability and degradation in plants. Plant Signal. Behav., 16(12), 1987767.

Zhao, H.; Chen, H.; Zhao, B. (2024). Glycolic acid addition enhances lead uptake and transport by Hydrangea macrophylla (Thunb.) Ser. of different plant ages. Environ. Technol. Innov., 36, 103877.

Zhi, H., Yu, M., Yao, J., Sun, C., Cui, B., Zhao, X., and Zeng, Z. (2020). A facile approach to increasing the foliage retention of pesticides based on coating with a tannic acid/Fe3+ complex. *Coatings*, *10*(4), 359.

Zhou, J.; Hu, Q.; Xiao, X.; Yao, D.; Ge, S.; Ye, J.; Xing, W. (2021). Mechanism of phosphate sensing and signaling revealed by rice SPX1-PHR2 complex structure. Nat. Commun., 12(1), 7040.

Zhu, H., Shen, Y., Cui, J., Li, N., Wang, C., Cui, B., and Cui, H. (2020). Avermectin loaded carboxymethyl cellulose nanoparticles with stimuli-responsive and controlled release properties. Industrial *Crops and Products*, 152, 112497.