Entry to the Stockholm Junior Water Prize 2024:

Electrospun nanofiber membranes for mixed microplastic and co-contaminants removal on seed germination and early plant growth

Students: Aggeliki Giorgalla
Eliana Christodoulou

Advisor: Andri Andreou

School: Apostles Peter and Paul Lyceum

Cyprus

1. Preliminary Matters

1a. Abstract

Over the past few years**,** the planet has been suffering from several environmental problems such as climate change and pollution. In recent years, plastic waste has been attracting more and more attention as a global environmental problem due to its wide range of uses and fields that are expanding year by year. When plastic products are decomposed to the environment, microplastics are left in the soil or the water, which is hazardous for wildlife. To prevent the catastrophic consequences of this contamination, research has been made to study the effects those contaminants have on plant growth. Those pollutants can also be antibiotics that have been disposed of to the landfills and then end up in the water. The present study aims to present the impact to the growth of a plant in the presence of MPs (PVC, PS) and antibiotic (SMX) either separately or mixed. MPs are recognized as a new form of pollutant that has attracted the attention of researchers worldwide. For the conduction of the study three types of plants were used: *Lepidium sativum, Sorghum saccharatum* and *Sinapis alba.* To study the effects the contaminants have on the plants the Phytotoxkit Microbiotest was used. The advantages of this toxicity bioassay compared to chemical analysis and many other bioassays are its speed, relative simplicity, and low cost. Lastly, the root and shoot length of each seed were measured to determine whether the presence of the contaminants caused a decrease or an increase to this length.

Additionally, electrospinning emerges as a promising technique for addressing water pollution challenges. Electrospun membranes offer a highly porous structure with selective retention capabilities, making them effective in filtering microplastics from water sources. Furthermore, electrospinning technology has advanced incorporating inorganic nanoparticulates within functional fibrous polymer matrices, enhancing their adsorption efficiency for removing contaminants from wastewater. This study highlights the potential of electrospinning as a sustainable solution for mitigating plastic pollution and other environmental hazards.

1b. Table of Contents

1c. Abbreviations and Acronyms

IWRC (International Water Research Center) · MPs (Microplastics) · NPs (Nanoplastics) · PS (Polystyrene) · PVC (Polyvinyl chloride) · SMX (Sulfamethoxazole) · CA (Cellulose acetate) · (SEM) Scanning Electron Microscopy · PE (Polyethylene)

1d. Acknowledgements

We would like to express our deepest appreciation to everyone who helped us complete our project. This work would not have been completed without the help and advice of people skilled in and deeply involved in this scientific subject. Regarding the experiments, we would like to especially thank Dr. Popi Karaolia and Ms. Andrea Naziri of IWRC Nireas.

We also want to thank the Department of Mechanical and Manufacturing Engineering at the University of Cyprus (Polymer and Polymer Processing Laboratories) and especially Dr. Theodora Krasia-Christoforou, Dr. Petri Papaphilippou and Ms Victoria Theodorou for their assistance with the electrospinning process.

2. Introduction

Plastics debris has recently received increasing attention as a global environmental issue because of its wide applications and yearly ascending fields (Fan et al., 2022; UNEP, 2015). The plastics discharged from various sources are further degraded into fragments with the diameter of < 5 mm (defined as microplastics (MPs)) through ultraviolet light, wind, wave action and abrasion in natural waters (GESAMP, 2015; Hidalgo-Ruz et al., 2012; Wright et al., 2013). MPs are considered a new form of pollutant that has attracted increasing attention from researchers worldwide, since 1970 (Cole et al., 2011). MPs characteristically have small particle sizes, large specific surface areas, and a high hydrophobicity. The large surface areas not only help the contaminant-laden microplastics carry harmful chemicals to the environment but also, organisms upon ingestion, and different metabolic pathways can transfer chemicals from the plastic surface to tissues (Agboola & Benson, 2021; Zhang et al., 2015). Studies have been extensively focused on the aquatic environment (Horton et al., 2017), but also MPs can enter the soil through landfills, agricultural mulching films, sewage irrigation and sludge, flooding, bioturbation, and diffuse atmospheric deposition (Blasing and Amelung, 2018; Steinmetz et al., 2016; Zhang et al., 2020c).

Persistent microplastics in water interact with aquatic life. It's crucial to study their interactions with other pollutants for ecological risk assessment. Microplastics in dams are globally concerning. Climate change exacerbates issues like soil moisture decline, affecting agriculture and water scarcity, which impacts regions like Cyprus, highlighting broader water scarcity challenges in Europe. Cyprus' example helps to show omens that might be echoed in other countries, who face the same problem. Our island suffers from the highest water stress level in Europe, particularly in years of excessive drought (Bixio, D et al 2008; Raso, J et al April 2013). Water scarcity is a significant concern in Cyprus due to limited supplies. Urban expansion and population growth underscore the need to reduce reliance on rainfall. Low precipitation is common, requiring the water system to efficiently manage reserves to avoid shortages. Saving water in dams allows for use across sectors, including agriculture and households, ensuring resilience during dry periods.

Antibiotic compounds and plastic materials are being used in an excessive way by people and consequently, plants are being exposed to harmful, toxic, and hazardous substances. Extensive research has been done on the potential negative effects of antibiotics absorbed by crop plants on human health (Grote et al. 2007; Kumar et al. 2005; Pan et al. 2014; Kang et al. 2013). Meanwhile, less research has been done on how antibiotics affect actual plants, particularly non-crop species. Typically, roots suffer the most damage and acquire the most antibiotics (Migliore et al. 2010), where they negatively affect root length, root elongation and the number of lateral roots with consequences for plant water uptake (Piotrowicz-Cieslak et al. 2010; Michelini et al. 2012).

Through intricate interactions, the presence of plastics can have several harmful impacts on soil organisms. Plastic particles with a minimum size of less than 100 μm are an emerging problem and have also been difficult to detect. MPs may act as a carrier for toxic substances, such as heavy metals and organic pollutants in terrestrial environments (Campanale et al., 2020; Enyoh et al., 2020; Verla et al., 2019). In addition, MPs and NPs, can accumulate on root surfaces and be transported into plants, causing substantial detrimental effects such as inhibition of growth and germination, alternation of antioxidative stress and decrease in photosynthetic rate (Gong et al., 2021; Pflugmacher et al., 2021). MPs/NPs can carry microbial pathogens, hydrophobic organic compounds, persistent organic pollutants, and heavy metals on their surface, which can generate undesirable effects on organisms. Their harmful effects are well documented. These include damage to cell membranes, tissues, and physiological processes.

Additionally, the interaction of MPs/NPs with pollutants causes aggregation, decreased bioavailability, and changes in the toxicity to the organism. Unequivocally, different antibiotics and plastics in soil can accumulate in citation and affect the functional features of crops and wild plant species either negatively, neutral, or favorably. It remains largely unclear what effects occur when using antibiotics and plastics together. To address this knowledge gap, we studied the effect of antibiotics along with MPs on three species of plants by watering them with water taken from two dams in Cyprus.

Currently, there is a limited amount of research dedicated to the technologies and their efficiency in removing microplastics from drinking water. These studies predominantly depend on costly methods initially designed for alternative uses but also investigated for MPs removal (D. Barcelo et al., 2020). This study aims to tackle the problem of MPs pollution in dams’ water by exploring a low-cost tap water filtration system, using an electrospun fiber membrane. It has been reported that the membranes prepared by electrospinning nanofibers offers several benefits including small diameter, large specific surface area that may provide additional adsorption sites, high porosity (reaching 80% or higher), strong connectivity, small pore size, high surface roughness, and low weight per gram. (Xue, J et al., 2019). The prespective of the MPs/NPs removal using electrospun nanofiber membranes is putting forward a new research and development roadmap. In our view, those membranes can reach a milestone in controlling MPs/NPs pollution in water in the next decades.

3. Materials and Methods

3.1 Testing hypothesis of the project

Does surface water that contain a mixture of MPs and antibiotics affect the growth of plants?

3.2 Materials and methods used

The Cypriot society has long grappled with intermittent droughts throughout its history, a challenge not unique to Cyprus but also affecting other nations worldwide due to climate change. This environmental issue, stemming from human actions, prompted a study on water quality in dams to assess the impact of accumulated microplastics and antibiotics on plants' biometric parameters. Given that dam water is utilized for both water supply and irrigation, particularly during dry periods, concerns have arisen among farmers regarding the sustainability of water used for crop cultivation. Therefore, we took samples from two different dams in Limassol province, Polemidia and Germasogia dam.

According to the Department of Water Development and the National Open Data Portal of Cyprus, the Polemidion Dam is in the Polemidia area. More specifically, it is located near the Limassol National Forest Park. The dam was built in 1965, making it the oldest dam on the island. The dam is 2,96 kilometres long and 45 metres deep. It also can contain 3 400 000 cubic metres of water. The water in the dam is collected from the Garyllis river which passes through the city of Limassol and flows into the sea. The water coming from the Polemidion dam is used for irrigation (citrus and table grapes).

The Germasogia Dam was built in 1968 on land that was owned by the Germasogia Municipality, and the communities of Akrounda and Finikaria in the Limassol district. It is built on the north borders of the municipality at a distance of 4 kilometres from the beach area. The dam takes in water from the Amatho River, which is of dirt type and has an altitude of 49 metres. The basin can store 13,5 million cubic metres of water to its extent of 110 hectares. The water coming from the Germasogia dam is used for irrigation (citrus and table grapes).

Polystyrene (PS) microplastics powder, average particle size: 900 μm purchased from Goodfellow Cambridge Limited (England, UK). Polyvinyl chloride (PVC) microplastics (unplasticised, powder, particle size: ≤ 250 μm (PVC)) were purchased from Goodfellow Cambridge Limited (England, UK). The selection of PS and PVC plastics was based on their frequent detection in the environment (Alimi et al., 2018). The concentrations of the MPs used were: PVC concentration (alone): 500 mg L^{-1}, PS concentration (alone): 500 mg L^{-1} and PVC + PS total concentration (together): 500 mg L^{-1}. Information about the microplastics used in the study is presented in Table 1.

Table 1

Microplastic characteristics used in this study.

Microplastics	**Abbreviation**	**Particle size (µm)**	**Behavior in water**
Polystyrene	PS	900	deposited at the surface of water
Polyvinyl chloride	PVC	≤ 250	deposited at the bottom of the petri dish

The antibiotic standard of sulfamethoxazole (SMX, CAS Number 723-46-6, molecular formula $C_{10}H_{11}N_3O_3S$, molecular weight 253,28 g mol^{-1}) was purchased from Fluka Analytical. It was of high purity grade and was used as received. The concentration of SMX used to inoculate the freshwater samples was 100 µg L^{-1}.

The phytotoxicity of the three types of freshwaters containing the micropollutants, was evaluated using the Phytotox kit (Microbiotests). This phytotoxicity test kit is intended for phytotoxicity screening of chemicals and other research applications. It contains all necessary materials to perform complete 3-day seed germination and early growth tests with three plant species: the monocotyl Sorghum saccharatum (Sorgho), the dicotyls Lepidium sativum (garden cress) and Sinapis alba (mustard), in three replicates. This cost-effective and user-friendly phytotoxicity assay strictly adheres to ISO Standard 18763.

The Phytotoxkit Microbiotest measures the decrease (or the absence) of germination, along with the growth of the roots after a few days of exposure of seeds to toxicants, in comparison to the controls in a reference water sample. The Phytotoxkit makes use of unique flat and shallow transparent test plates composed of two compartments, the lower one of which will be filled with water. Seeds of the selected test plants are positioned near the middle ridge of the test plate, on filter paper placed on top of the hydrated soil. After closing the test plates with their transparent cover by means of a unique click system, the test plates are placed vertically in a holder and incubated at 25 °C (+/- 1 °C). At the end of the incubation period, a picture was taken of the test plates with the germinated plants and the root and shoot lengths were recorded. The successful germination of the plant seeds was also recorded. The tested samples using the Phytotoxkit Microbiotest are shown in Figure 1.

Table 2

The examined samples of this study.

Polemidia dam water			
Code	**Examined sample characteristics**	**Code**	**Examined sample characteristics**
1	Control (no contaminants)	**5**	all
2	PVC	**6**	PVC + PS
3	PS	**7**	PVC + SMX
4	SMX	**8**	PS + SMX
Germasogia dam water			
9	Control (no contaminants)	**13**	all
10	PVC	**14**	PVC + PS
11	PS	**15**	PVC + SMX
12	SMX	**16**	PS + SMX
17	Tap Water		

To calculate the percentage inhibition of seed germination and root growth, the following formula was used:

% Inhibition of germination/root and shoot growth = $\frac{A-B}{A} \times 100$

Where: A=Control sample and

B=Test sample

Statistical analysis of the % inhibition of germination/root and shoot growth was done using Excel software.

Fig. 1. Pictures of the Phytotoxkit Microbiotest plant growth during the experiment. (A shows the seed germination process during day 1 of the experiment, B shows the incubation of the test plates in the incubator at 25 ^{o}C and C and D show how the roots and shoots of the plants grow)

The examined samples include control samples (tap water and each dam water separately without any addition of MPs or SMX), and the following samples spiked with one or two microplastics together and with/without the antibiotic compound. The examined samples are shown in Table 2.

4. Results and Discussion

Based on the obtained seed germination results, we calculated the average root and shoot length of all germinated seeds for each test plate.

From the graph's results (Fig. 2), it can be deduced that for the root length growth of plants B and C, there was an increase, in contrast to the results of the root length growth of plant A, where there was a general decrease to the growth with two exceptions.

The root length growth of plant B reached the significant peak of 200% in the combination of the microplastic PS and the antibiotic while the other two plant species did not show a significant change to their growth. Furthermore, Plant B's root length depicts a general rise in its percentage growth compared to the control sample, but it remains typically stable. In the presence of sulfamethoxazole, plants A and C respond in the same way as the root was escalated by 22-23%. Meanwhile, Plant C presents an abnormality in its growth when it comes to the presence of all the contaminants together, where it remains unchanged, although the other two plant species were affected by that combination.

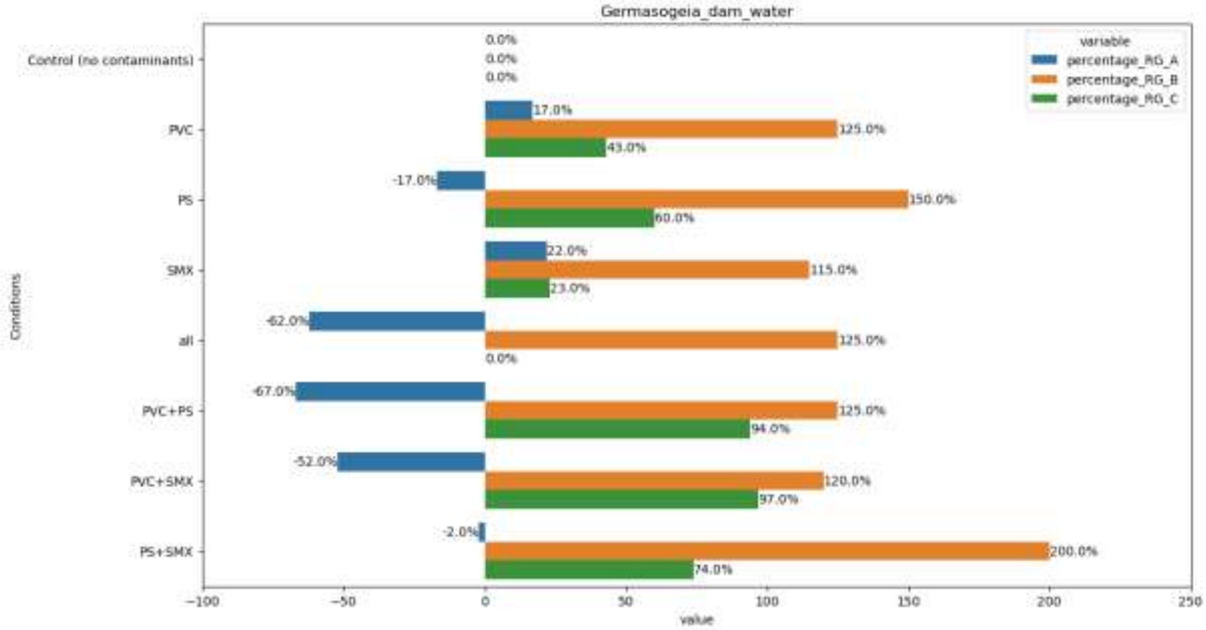

Fig. 2. Average length of root growth for *Lepidium sativum* (Plant A), *Sorghum Saccharatum* (Plant B) and *Sinapis Alba* (Plant C) in the addition of one or two microplastics together and with/without the SMX irrigated with Germasogeia dam water.

The effect from PVC on plant A (17%) is the exact opposite to the percentage root length growth of plant A in presence of PS (-17%). However, the mixture of PVC+SMX resulted in a greater increase in the root length development of plant A compared to PS+SMX, while the opposite is observed in plants B and C. All in all, there are not any serious irregularities in the way each plant's root responds to the various types of microplastics and co-contaminants they were exposed to. To conclude, when the plants were irrigated with water from the Germasogeia dam, their behavior did not vary significantly from contaminant to contaminant. Plant C showed a steady increase, as did plant B, while plant A exhibited some fluctuations in its percentage growth, as it experienced both increases and decreases.

The second graph (Fig. 3) of Polemidia dam water indicates a slight positive effect from PVC on plant A, while plant B showed a quite bigger increase (8%, 22%) compared to plant C, which exhibits a decrease of 9%. All the co-contaminants, combined or separated, had an enormous negative response on plant A by 50%, except for SMX, which had a positive impact. However, Plant B had the most positive reaction of all the other plants when mixed with the co-contaminants, except for the mixture of PVC+SMX, which had the slightest negative impact on it.

In conclusion, the graphs show that most contaminants affected the plants' root length growth more negatively, excluding plant B, which had small increases when the water was mixed with the co-contaminants.

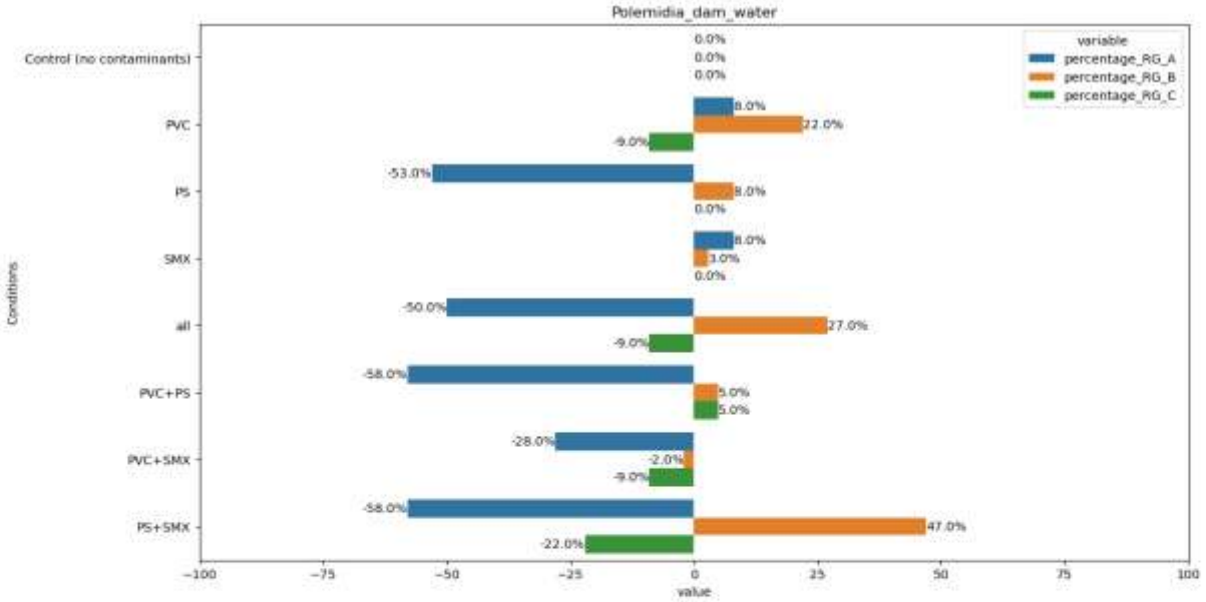

Fig. 3. Average length of root growth for *Lepidium sativum* (Plant A), *Sorghum Saccharatum* (Plant B) and *Sinapis Alba* (Plant C) in the addition of one or two microplastics together and with/without the SMX irrigated with Polemidia dam water.

The results obtained from the measurements of shoot length growth of the plant species (Fig. 4), when irrigated with Germasogeia dam water, are primarily positive. Nevertheless, a decrease in shoot growth is observed under the combination of PVC with SMX. Moreover, the three combinations of contaminants seem to negatively influence the shoot growth of the seeds of plant A, while the mixtures of PS + SMX, PVC with SMX, and SMX alone generally accelerated the shoot length growth.

The greatest percentage increase in growth is 65% when plant B was watered with the sample containing the combination of PS+SMX. It is important to note the slight changes in the shoot lengths for both plants A and C in the presence of the contaminant PVC, while Polystyrene did not affect Lepidium Sativum's growth at all.

The conclusion deduced from the graph's results is that while the water from Germasogeia dam is mixed with contaminants, combined, or alone, plant C's shoot growth is always increased, with the significant peak of PS at 37%.

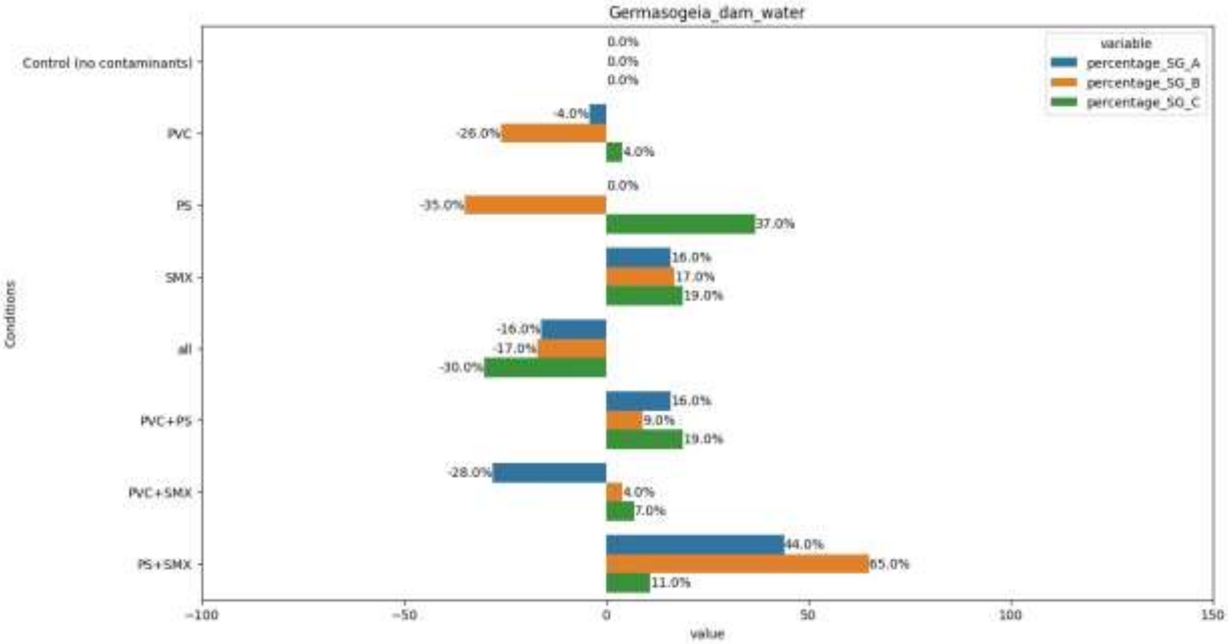

Fig. 4. Average length of shoot growth for *Lepidium sativum* (Plant A), *Sorghum Saccharatum* (Plant B) and *Sinapis Alba* (Plant C) in the addition of one or two microplastics together and with/without the SMX irrigated with Germasogeia dam water.

The seeds irrigated with the Polemidia sample (Fig. 5) mostly show a reduction in shoot length, especially in the presence of PS, with the lowest value observed in the combination of PS and SMX (-71%). Additionally, plant A has a negative effect in almost every combination of the co-contaminants, except for a slight increase in PVC (+3%) and PS (+25%).

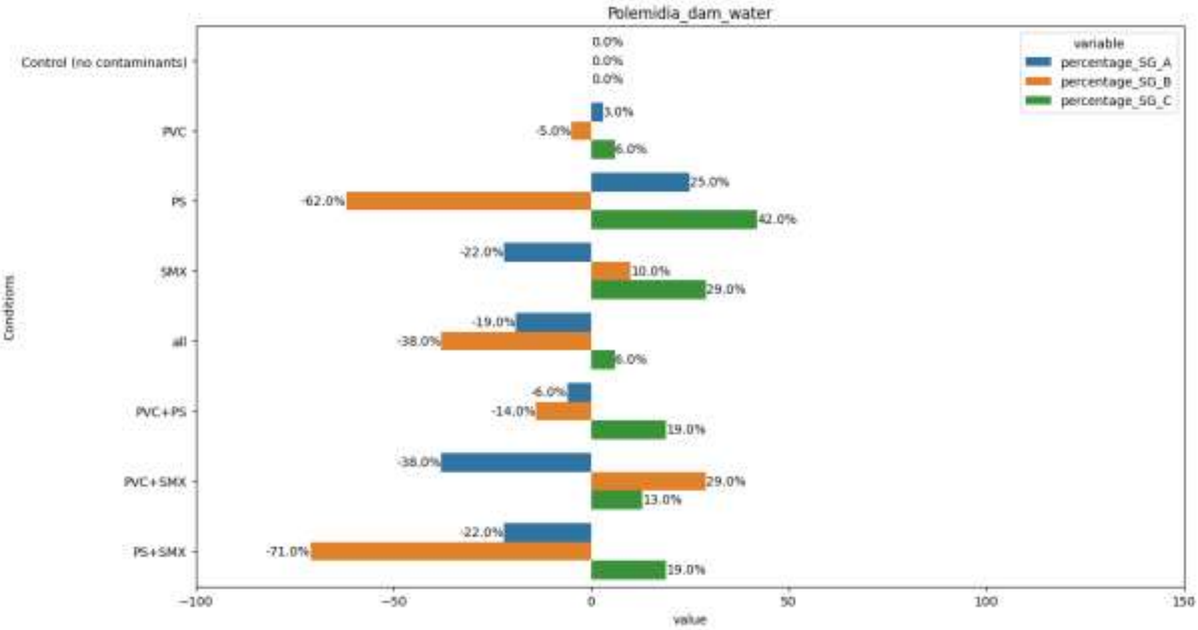

Fig. 5. Average length of shoot growth for *Lepidium sativum* (Plant A), *Sorghum Saccharatum* (Plant B) and *Sinapis Alba* (Plant C) in the addition of one or two microplastics together and with/without the SMX irrigated with Polemidia dam water.

Despite some negative values, SMX alone, as well as the combination of PVC and SMX, caused an increase in shoot thickness only in plants B and C. Plant B exhibited the most negative reactions compared to the other two plants when irrigated with microplastics, while plant A predominantly experienced a decrease in shoot length growth. The water from Polemidia had a beneficial effect only on the growth of the plant shoots; PS alone had the highest percentage increase (42%), while PVC and the combination of all pollutants had the lowest percentage increase (+6%) on plant C, although they still negatively impacted the other plants (-19%, -38%).

Prior to conducting the research, we hypothesized that MPs and SMX would only cause negative effects on root growth. However, our study revealed that MPs and SMX can have beneficial effects on some plants, indicating a hormetic response. This suggests that the hormesis effect may disrupt natural ecosystems, as several plants may not grow normally due to high concentrations of MPs and SMX. We concluded that the effect of using MPs and SMX on plant growth depends on their dosage and how different plant species react to them.

4. 1 Electrospinning: Effective solution in removing contaminants from wastewater

Electrospinning is an advanced fiber preparation technology that uses the interaction between the liquid and electric field to generate polymeric fibers, with diameters ranging from the nanoscale to the microscale. The polymers can be synthetic or natural, and composite materials can also be used (Kang, S.X. et al., 2020). The custom-made electrospinning apparatus (available in the Department of Mechanical and Manufacturing Engineering, University of Cyprus) that was used in the present study and a schematic of the electrospinning process are shown in Figure 6.

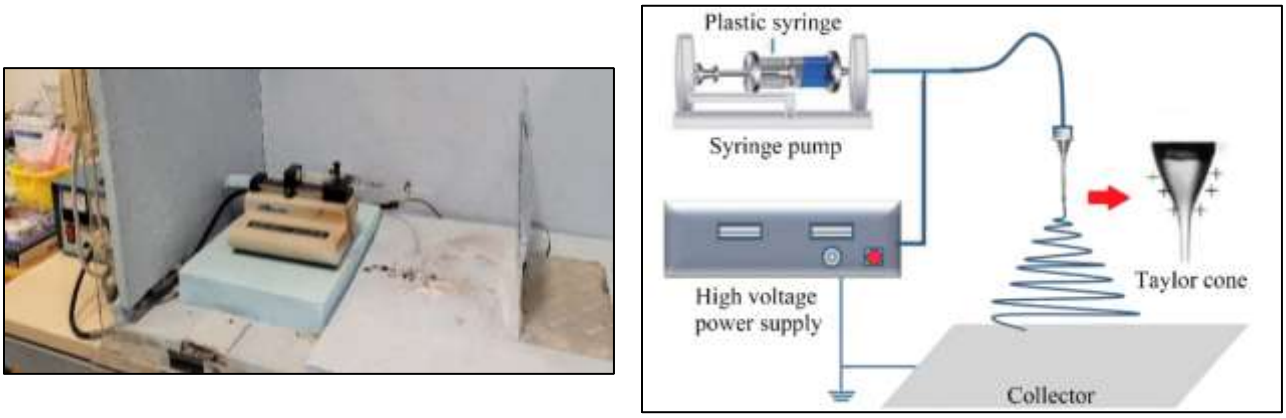

Fig. 6. The mechanism of electrospinning. Reprinted from Chen, K et al., 2019.

4. 1. 1 Working Process and Principle of Electrospinning

A typical electrospinning setup consists of three main parts: a syringe pump, a high-voltage power supply, and a conductive collector. In this specific process, a polymer solution is placed in the syringe, and a high voltage (typically 5-50 kV) is applied between the tip of the needle and the grounded metallic collector. The solution flow rate is maintained constant during the whole process, using a syringe pump, while simultaneously applying high voltage. This results in the formation of a droplet at the tip of the needle, experiencing two types of forces: electrostatic repulsive force and surface tension (Teo W. et al., 2006). Under the influence of these electrostatic interactions, the droplet at the tip forms a conical structure called the Taylor Cone. At a critical voltage, the repulsive force of the charged polymer overcomes the surface tension of the solution, and a charged jet is ejected from the tip of the Taylor Cone, moving towards the opposite electrode, and gradually thinning as it reaches the collector. As it travels towards the opposite electrode, the solvent evaporates (or the droplet solidifies), and solid fibers with diameters ranging from micrometers to nanometers are deposited with random or aligned orientation in a mesh-like form. The main advantage of this technique is that it can produce extremely fine fibers with high aspect ratio and high porosity if needed (Zhang H. et al., 2010). Moreover, it is noteworthy mentioning that the electrospinning technique has already reached the industrial sector, and many companies already produced different products consisting of nano- and microfibers (Pharmaceutics. 2021).

4. 2 Parameters in the electrospinning method

The electrospinning process is influenced by several parameters, which can be categorized into the following three categories: solution parameters, process parameters, and environmental parameters. Solution parameters include viscosity, conductivity, molecular weight, and surface tension, while process parameters encompass applied electric field, distance between the nozzle and collector, and the feed rate of the solution. Each of these parameters significantly affects the morphology and structure of the nanofibers, and proper management of these parameters allows for obtaining nanofibers of desired morphology and diameter. Environmental parameters, such as humidity and temperature, also play a significant role in determining the structure of nanofibers (Jin XD. et al., 2012).

4.2.1 Solution Parameters: Viscosity and Polymer Concentration

Concentration and the type of polymer are among the most fundamental parameters as they are directly related to the viscosity of the solution. An increase in concentration results in an increase in the viscosity of the solution. Depending on the polymer being processed, the viscosity value must be appropriately adjusted to produce the desired fibers, as not all viscosity values are suitable for every polymer. Thus, each polymer will yield the desired result within a different range of viscosity values.

There are numerous types of materials that could be used in the electrospinning technique, and it is essential to consider their individual properties depending on the applications for which they are intended. For this study, the material we used to produce ultrathin fibers is cellulose acetate (CA), which is a naturally-derived polymer (cellulose derivative) of low cost, that can be easily processed in solution and it is highly electrospinnable. CA stands out as a crucial derivative of cellulose due to its wide range of applications and properties. It is derived from natural and renewable resources, making it an environmentally friendly option. One of its key advantages lies in its low toxicity and biodegradability (Zugenmaier, 2004). Additionally, cellulose acetate (CA) has been significantly utilized in membrane technology, particularly in water and wastewater treatment. CA membranes are preferred over other polymers because of their favorable hydrophilic characteristics.

4.2.2 Membrane Characterization

The morphology of membranes produced by the electrospinning method was analyzed using a scanning electron microscope (SEM). The geometrical requirements of produced fibers such as fiber diameter, diameter distribution and orientation were also determined.

SEM images were analyzed to elucidate the structure of the electrospun fibers. Figure 7 shows the images of the membrane surfaces with an applied voltage 10kV. SEM images were taken at magnification of x200, x 1000 and x5000. This allowed for a closer inspection of the morphology of the membranes and for determining the fiber diameter. The average fiber diameters and their distribution were measured using an image analysis software (ImageJ) by measuring at least 40 fibers in SEM images. This was found to be 1,292 ± 0,344μm.

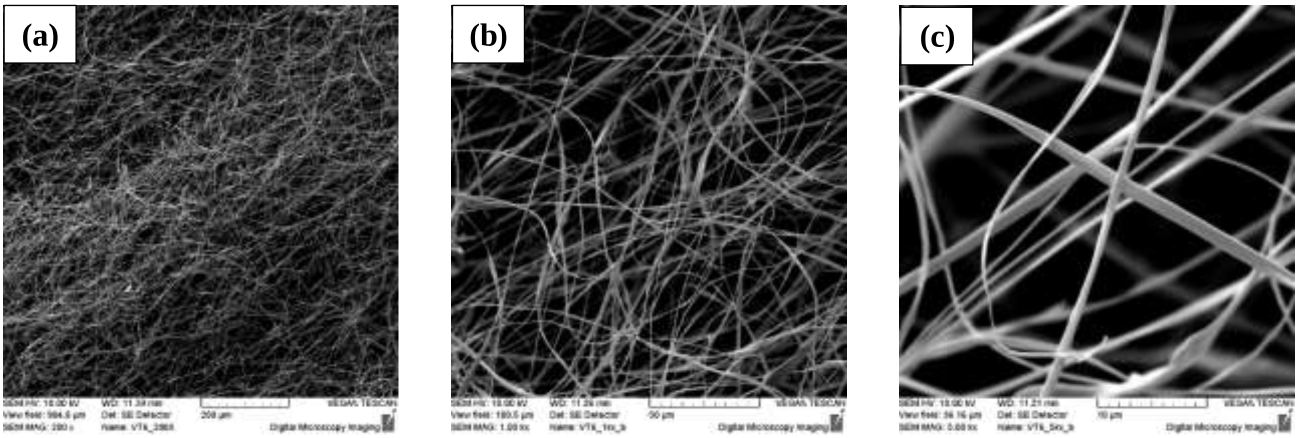

Fig. 7. SEM images of CA fibrous membranes with a magnification of (a) x200, (b) x1000 and (c) x5000.

Subsequently, MPs were added to water, and the filtration test was performed using CA electrospum membranes and normal filter paper as shown in Figure 8(a). Since the MPs we used are large (average diameter for PS is about 900 μm and for PVC ≤ 250 μm), they were retained in both filters as expected (Figure 8(b)).

After subjecting the electrospun fibrous CA membrane to the water filtration test, no discernible alterations were detected in its structure or composition. This outcome underscores the remarkable mechanical resilience and hydraulic stability exhibited by these electrospun fibrous CA membranes.

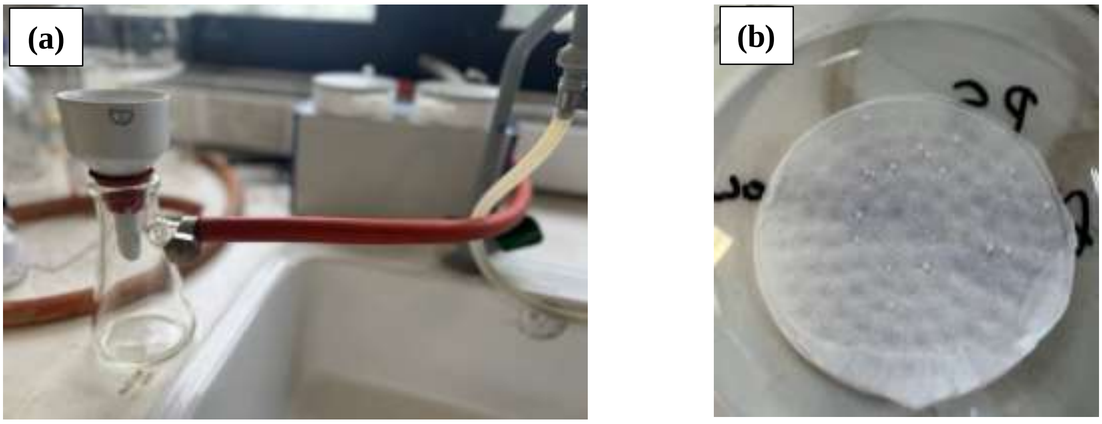

Fig. 8. (a) Water filtration test, (b) MPs in CA nanofiber membranes after water filtration test

We used SEM to observe if on the CA electrospun membranes the MPs, including Polystyrene (PS), poly(vinyl chloride) (PVC) and polyethylene (PE), adhere better compared to the normal filter paper. SEM images of the normal filter paper obtained after filtration are shown in Figure 9 and the ones corresponding to the CA electrospun membranes are provided in Figure 10.

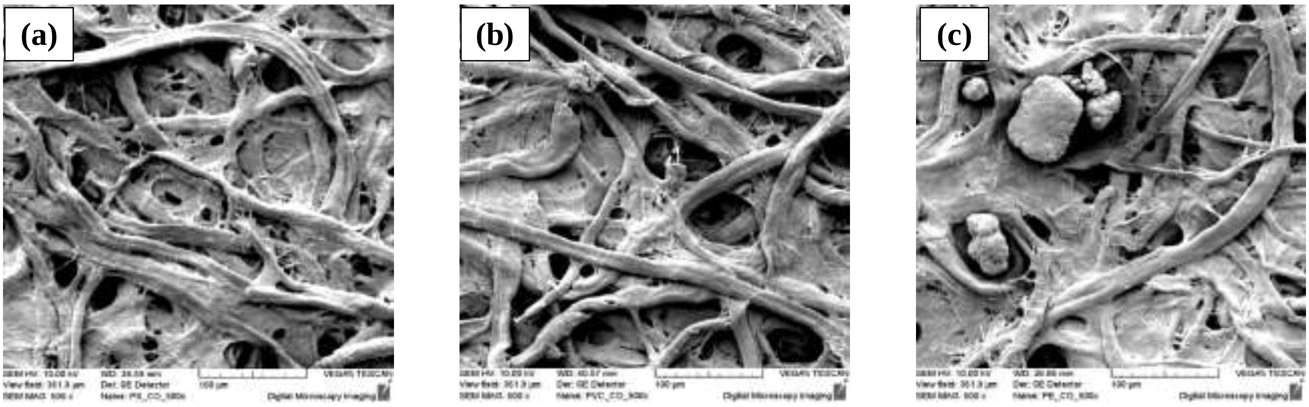

Fig. 9. SEM images of the surface of the normal filter paper with a magnification of x500: (a) PS, (b) PVC and (c) PE.

From the results obtained, it appears that the produced membranes selectively retain PE microplastics followed by PVC, whereas it appeared that PS MPs could not adhere on the membranes and not at all from PS. However, by changing the chemical composition of the electrospun membranes, interactions with PS could potentially be enhanced.

Although not tested in this study, it is noteworthy mentioning that based on existing literature, electrospun nano- and microfibers can be successfully used as substrates for the adsorption of antibiotics and other organic contaminants from wastewater (Cao X. et al., 2022, Kun Zhao et al., 2021).

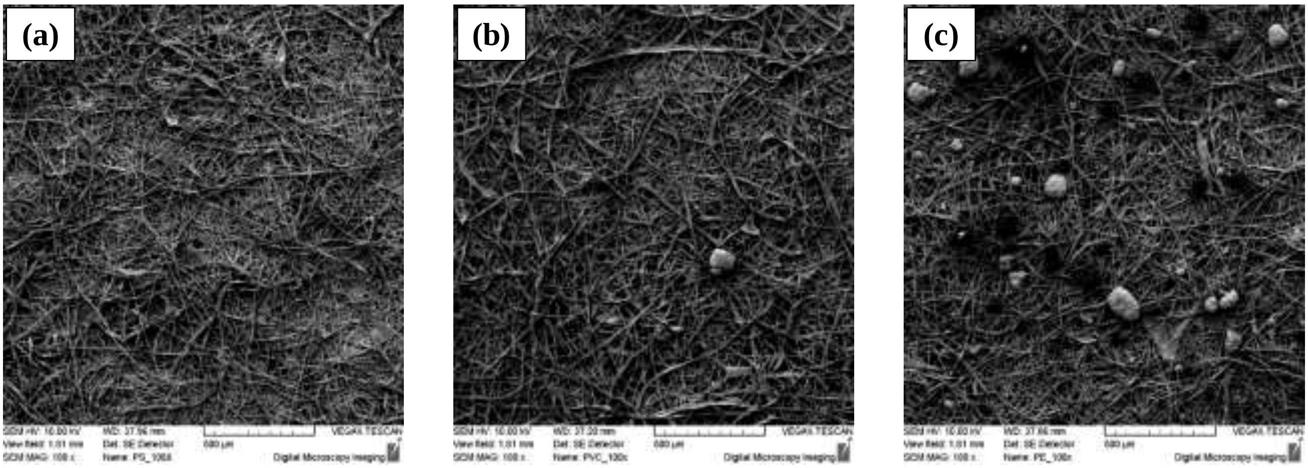

Fig. 10. SEM images of the surface of the CA nanofiber membranes with a magnification of x100: (a) PS, (b) PVC and (c) PE.

5. Conclusion

In conclusion, our study sheds light on the complex interactions between contaminants and plant growth, highlighting both expected and unexpected outcomes. We observed varied responses among different plant species to microplastics and co-contaminants, with some exhibiting hormesis effects, suggesting the need for nuanced considerations in environmental risk assessments.

Furthermore, our investigation into the potential application of electrospinning technology in wastewater treatment reveals promising results, demonstrating the resilience and selective retention capabilities of electrospun fibrous membranes for microplastic removal. However, further research is warranted to optimize electrospinning techniques and explore their broader environmental applications. Electrospinning as a technique can be used not only as a mean of shifting MPs but also antibiotics, which are also organic compounds. As a result, functionalized fibrous nanocomposites that could be used as extremely efficient adsorbents in water-remediation processes are produced by the opportunity to incorporate inorganic nanoparticulates with distinct properties and functions within functional electrospun fibrous polymer matrices (Homocianu, M. et al. Rev. 2020). Also, the use of magnetic nanoparticles as nanofillers in fibrous membrane adsorbents based on electrospun polymers has resulted in enhanced adsorption efficiency and the possibility of magnetic recovery by the application of an external magnetic field. of these. Therefore, removing the antibiotics from the water may also be accomplished with the use of magnetic nanofibers.

Overall, our study contributes to the growing body of knowledge on contaminant-plant interactions and underscores the importance of interdisciplinary approaches in addressing environmental challenges for the well-being of both ecosystems and human communities.

6. References

Agboola, N.U. Benson- Physisorption and chemisorption mechanisms influencing micro (nano) plastics-organic chemical contaminants interactions: a review Front. Environ. Sci., 28 (2021), 10.3389/fenvs.2021.678574

Alimi, O.S., Budarz, J.F., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nano-plastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sei. Technol. 52, 1704-1724.

Bixio, D. Cyprus without Water? One Island, One Problem and Some Related Challenges; European Commission: Brussels, Belgium, 2008.

Blasing, M., Amelung, W., 2018. Plastics in soil: analytical methods and possible sources. Sci. Total Environ. 612, 422–435.

Campanale, C.; Massarelli, C.; Savino, I.; Locaputo, V.; Uricchio, V.F. A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. Int. J. Environ. Res. Public Health 2020, 17, 1212. https://doi.org/10.3390/ijerph17041212

Cao X., Chen W., Zhao P., Yang Y., Yu D.-G. Electrospun porous nanofibers: Pore-forming mechanisms and applications for photocatalytic degradation of organic pollutants in wastewater. Polymers. 2022;14:3990. doi: 10.3390/polym14193990.

Chen, K.; Chou, W.; Liu, L.; Cui, Y.; Xue, P.; Jia, M. Electrochemical Sensors Fabricated by Electrospinning Technology: An Overview. Sensors 2019, 19, 3676.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62 (12), 2588e2597.

D. Barcelo, Y. Pico, Case studies of macro- and microplastics pollution in coastal waters and rivers is there a solution with new removal technologies and policy actions? Case Stud. Chem. Environ. Eng. (2020) 100019, https://doi.org/10.1016/j.cscee.2020.100019.

Enyoh CE, Verla AW,, Isiuku BO, Verla EN, Enyoh EC. Effect of macro- and micro- plastics in soil on growth of juvenile lime tree (Citrus aurantium) Imo State University; Nigeria: 2020.

Fan, Y.V., Jiang, P., Tan, R.R., Aviso, K.B., You, F., Zhao, X., Lee, C.T., Klemes, J.J., 2022. Forecasting plastic waste generation and interventions for environmental hazard mitigation. J. Hazard. Mater. 424, 127330.

GESAMP, 2015. Sources, fate and effects of microplastics in the marine environment: a global assessment. In: Kershaw, P.J. (Ed.), IMO/FAO/UNESCO-IOC/UNIDO/-WMO/ IAEA/UN/UNEP/UNDP. Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection Reports and Studies. GESAMP, pp. 90–6.

Gong Y, Varnau R, Wallner E, Acharya R, Bergmann DC,Cheung LS (2021) Quantitative and dynamic cell polarity tracking in plant cells New Phytologist 230:867–877.

Grote M, Schwake-Anduschus C, Michel R, et al. 2007. Incorporation of veterinary antibiotics into crops from manured soil. Landbauforschung Völkenrode 57:25–32.

Hanif MA, Ibrahim N, Dahalan FA, Md Ali UF, Hasan M, Jalil AA. Microplastics and nanoplastics: recent literature studies and patents on their removal from aqueous environment. Sci Total Environ 2022; 810:152115.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46 (6), 3060–3075.

Homocianu, M.; Pascariu, P. Electrospun Polymer-Inorganic Nanostructured Materials and Their Applications. Poly. Rev. 2020, 60, 493–541.

Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141.

Jin XD., Doctoral thesis, development and characterization of carbon nanotube based functional nanocomposites, Shinshu University, Ueda, 2012.

Kang DH, Gupta S, Rosen C, et al. 2013. Antibiotic uptake by vegetable crops from manure-applied soils. Journal of Agricultural and Food Chemistry 61:9992–10001.

Kang, S.X.; Hou, S.C.; Chen, X.W.; Yu, D.G.;Wang, L.; Li, X.Y.;Williams, G.R. Energy-saving electrospinning with a concentric teflon-core rod spinneret to create medicated nanofibers. Polymers 2020, 12, 2421.

Kumar K, Gupta SC, Baidoo SK, Chander Y, Rosen CJ. 2005. Antibiotic uptake by plants from soil fertilised with animal manure. Journal of Environmental Quality 34:2082–2085.

Kun Zhao, Shi-Xiong Kang, Yao-Yao Yang, Deng-Guang Yu. 2021. Electrospun Functional Nanofiber Membrane for Antibiotic Removal inWater: Review.

Michelini L, Reichel R, Werner W, Ghisi R, Thiele-Bruhn S. 2012. Sulfadiazine uptake and effects on Salix fragilis L. and Zea mays L. plants. Water Air and Soil Pollution 223:5243–5257.

Migliore L, Rotini A, Cerioli NL, Cozzolino S, Fiori M. 2010. Phytotoxic antibiotic sulfadimethoxine elicits a complex hormetic response in the weed Lythrum salicaria L. Dose–Response 8:414–427.

Pan M, Wong CKC, Chu LM. 2014. Distribution of antibiotics in wastewater-irrigated soils and their accumulation in vegetable crops in the Pearl River Delta, Southern China. Journal of Agricultural and Food Chemistry 62:11062–11069.

Pharmaceutics. 2021 Feb; 13(2): 286. https://onlinelibrary.wiley.com/doi/10.1002/mame.201200290).

Pflugmacher, S., Huttunen, J. H., von Wolff, M. A., Penttinen, O. P., Kim, Y. J., Kim, S., et al. (2020). Enchytraeus crypticus avoid soil spiked with microplastic. Toxics 8 (1), 10. doi:10.3390/toxics8010010

Piotrowicz - Cieślak AI, Adomas B, Nałęcz - Jawecki G, Michalczyk DJ. 2010. Phytotoxicity of sulfamethazine soil pollutant to six legume plant species. Journal of Toxicology and Environmental Health-Part a-Current Issues 73:1220–1229.

Raso, J. Updated Report on Wastewater Reuse in the European Union; European Commission: Brussels, Belgium, April 2013.

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tr¨oger, J., Mu˜noz, K., Fr¨or, O., Schaumann, G.E., 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci. Total Environ. 550, 690–705.

Teo W. E., Ramakrishna S., A review on electrospinning design and nanofibre assemblies, Nanotechnology, 2006.

United Nations Environment Programme (UNEP), 2015. Massive Online Open Course (MOOC) on Marine Litter. UNEP-University of the Netherlands, UNEP/GPML/GPA/ OU/GUPES marinelittermooc.org/learn/marine-litter-mooc-october-2015.

Verla AW, Enyoh CE, Verla EN (2019) Uptake of microplastics by plant: a reason to worry or to be happy? World Sci News 131:256–267.

Wang R, Zhang L, Chen B, Zhu X. Low-pressure driven electrospun membrane with tuned surface charge for efficient removal of polystyrene nanoplastics from water. J MEMBRANE SCI 2020;614:118470.

Water 2014, 6, 2898-2928; doi:10.3390/w6102898 - Water Scarcity in Cyprus: A Review and Call for Integrated Policy Anastasia Sofroniou 1,* and Steven Bishop 2

Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, R1–R2.

Xue, J.; Wu, T.; Dai, Y.; Xia, Y. Electrospinning and electrospun nanofibers: Methods, materials, and applications. Chem. Rev. 2019, 119, 5298–5415.

Zhang H, Xu L, Yang F, Geng L , The synthesis of polyacrylonitrile/carbon nanotube microspheres by aqueous deposition polymerization under ultrasonication, Carbon, 2010.

Zhang, W., Ma, X., Zhang, Z., 2015. Persistent organic pollutants carried on plastic resin pellets from two beaches in China. Mar. Pollut. Bull. 99, 28e34.

Zhang, Q., Zhao, Y., Du, F., Cai, H., Wang, G., Shi, H., 2020c. Microplastic fallout in different indoor environments. Environ. Sci. Technol. 54 (11), 6530–6539.

Zugenmaier, P., 2004. Characterization and physical properties of cellulose acetates. Macromol. Symp. 208, 81–166.