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Using the rhizofiltration ability of *Colocasia esculenta* to mitigate impacts of diuron without affecting its food consumption

Pierre-Alexandre Deyris, Franck Pelissier, Claire M. Grison, Claude Grison ^{*} 

Laboratory of Bio-Inspired Chemistry and Ecological Innovations, UMR 5021, CNRS-University of Montpellier 34790 Grabels, France

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ABSTRACT

In the last 30 years, the use of herbicides worldwide has doubled and these products were dispersed in soil and water. Many cases of contamination of tropical aquatic ecosystems were reported such as the case of diuron in South East Asia, Pacific and Africa for food crops such as pineapple. In parallel, taro (*Colocasia esculenta* or *C. esculenta*) large-scale cultivation is well established and the *C. esculenta* tubers consumption falls within local culinary uses. Here we propose a nature-based solution to mitigate the impact of diuron herbicide on tropical aquatic ecosystem. The aim of this perspective article is to illustrate the ability of cultivated plant *C. esculenta* to phytoaccumulate diuron pollutant by rhizofiltration. The resulting *C. esculenta* underwent several treatment steps to be suitable for precise diuron quantification. Analyses showed that the heart of the tubers contained less diuron than the recommended European standards and thus, could be still edible by local population which confirms the compatibility of the uses.

1. Introduction

The increase of world population irretrievably leads to the development of intensive agriculture. For the period between 1991 and 2021, the global use of pesticides worldwide doubled from 1.8 to 3.6 Mt (FAO stat, 2024). While the use of pesticides improves production yields and reduces the agricultural labour, the consequences on non-targeted organisms and the environment is a serious issue (Gensch et al., 2024). Among the huge quantity of pesticides used in 2021, 50 % were herbicides (FAO stat, 2024). Diuron is a photosystem II (PSII) inhibiting herbicide which is currently authorised in many countries around the world and is considered as problematic for risk management and remediation efforts of aquatic ecosystems (Yang et al., 2022). To highlight these statements, studies on the Great Barrier Reef (GBR) in Australia showed that contamination by PSII inhibiting herbicides, was mainly delivered in a dissolved state in water from river floods (Taucare et al., 2022). A recent article estimated that up to 42 % of aquatic species are affected by these herbicides (Warne et al., 2023), which make them identified as priority pollutants in the GBR (Davis et al., 2014). These pollutants were also found in sediments stemmed from several reef provinces (Brodie et al., 2010; Haynes and Michalek-Wagner, 2000), showing the extent of risks to coastal wetland habitats (Davis et al., 2013) and more widely to marine waters around the GBR (King et al.,

2013; Skerratt et al., 2023; Warne et al., 2023). Diuron affects the photosynthesis of the dinoflagellate symbiont of coral species (Salvat et al., 2016; Ukeles, 1962), which is one of the main causes of coral bleaching (Flores et al., 2021), even at a concentration <1 part per billion (Salvat et al., 2012). This herbicide particularly affects the breeding of phytoplankton (Berard and Pelte, 2005) and also affect the seagrass beds present in the Australian lagoon (Ramade and Roche, 2006), by rapidly inhibiting helobial photosynthesis at concentrations varying from 0.1 $\mu\text{g.L}^{-1}$ to 100 $\mu\text{g.L}^{-1}$ (Haynes and Michalek-Wagner, 2000; Negri et al., 2015). Diuron is also harmful to non-targeted organisms such as fishes (Zaluski et al., 2022), a widely distributed tropical diatom *Chaetoceros muelleri* (Thomas et al., 2020), marine bivalves such as the Pacific oyster *Crassostrea gigas* (Luna-Acosta et al., 2012) and microalgae *Tisochrysis lutea* and *Tetraselmis sp* (Flores et al., 2024). These data illustrate the ecotoxicity of diuron in the aquatic environment. Its toxicity on human health is equally worrying. Diuron was finally banned from use in France in 2008 (Pineau et al., 2017). According to the European Chemistry Regulation (ECHA) (Infocard, 2023), diuron is very toxic to aquatic life, with long-term effects, is harmful if swallowed, is suspected of causing cancer and may cause organic damage in case of prolonged or repeated exposure. It is currently evaluated as an endocrine disruptor. If Europe limited or forbade the use of diuron, this is not the case in other parts of the world. Several countries located in East

^{*} Corresponding author.

E-mail address: claude.grison@cnrs.fr (C. Grison).

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Asia, Oceania or Africa still continue to use this herbicide for agricultural purposes. Diuron has been found in soils, rivers and nearshore waters in Malaysia (Kamarudin et al., 2020), Philippines (Casimero et al., 2022), Thailand (Tantarawongsa and Ketrot, 2019), Japan (Kaonga et al., 2015), China (Liu et al., 2010) and Nigeria (Cyprian and Onuba, 2019). South Pacific islands such as Papua New Guinea and Solomon Islands (Skerratt et al., 2023), French Polynesia (Surchat et al., 2021), Fiji, Tonga and Australia (Warne et al., 2023) are also concerned. Most of these countries possess the commonality of still using diuron in agriculture but they also are large scale taro (*Colocasia esculenta* or *C. esculenta*) producers. The production is estimated at >2.8 Mt in 2022 (FAO stat, 2024). *C. esculenta* plant, belonging to the *Aracea* family, is an ancient and widespread plant which can be found mainly in tropical countries (Lebot and Ivančić, 2022). Historically, *C. esculenta* is originated from east Asia and spread naturally from India to Melanesia. Since 3000 years, *C. esculenta* cultivars were propagated from New Guinea to Pacific islands by Lapita people and Polynesian sailors (Lebot and Ivančić, 2022) then over the world (Tanimoto and Matsumoto, 1986). *C. esculenta* is a plant of cultural and dietary importance (Bambridge et al., 2017). Its natural habitat is wetlands (Fig. 1, A&B) and its well-developed root system (Fig. 1, C) makes it an ideal candidate for rhizofiltration experiments. The capacity of aquatic plants to phytoaccumulate inorganic pollutant such as heavy-metals or cationic organic pollutants such as dyes is well-known (Kristanti et al., 2021). This results from an ionic interaction between the carboxylates groups contained on roots surface and the cationic group on dyes. Little works have been devoted to the rhizofiltration of organic non-ionic pollutants such as persistent organic pollutants. For example, *Phragmites sp.* and *Heliconias sp.* are able to phytoaccumulate bisphenol A and nonylphenols up to 73.3 % efficiency (Toro-Vélez et al., 2016). *Acorus gramineus* showed good capacities to uptake organophosphates and organochlorines from water from 88 to 93 % efficiency in 5 days (Chuluun et al., 2009). Water hyacinth *Eichhornia crassipes* is able to remove the insecticide malathion and the anti-inflammatory drug piroxicam from water with respectively 67.6 and 99.1 % yields (Rodríguez-Espinosa et al., 2018). This plant also shows great capacity to sequester caffeine and ibuprofen with >80 % efficiency (De Oliveira et al., 2019). Concerning the capacity of *C. esculenta* to phytoaccumulate pollutants by rhizofiltration, several articles report the interest of *C. esculenta* in phytoremediation studies.

They can accumulate respectively 23.2, 31.79 and 47.32 mg.kg⁻¹ of Pb (II), Cr (VI) and total Cr in a controlled environment with very low translocation factors. They can therefore be qualified as accumulators of these toxic metallic elements (Madera-Parra et al., 2015). *C. esculenta* plants are able to reduce the nitrate and phosphate content of domestic wastewater and resist a Chemical Oxygen Demand (COD) of up to 1650 mg.L⁻¹ (Bindu et al., 2008). However, the ability of *C. esculenta* to clean up environments contaminated by organic pollutants has never been described. Considered essential vegetables in tropical countries, the cultivation of *C. esculenta* in small plots irrigated by a multitude of small canals, predispose them to play an interesting role in the capture of organic pollutants such as diuron.

Here, we propose a solution that is inspired by the concept of nature-based solutions to sustainably protect tropical aquatic ecosystems from herbicide pollution, reconciling large-scale feasibility, economic benefits and respect for biodiversity. The proposed solution is the use of an indigenous and humid zone plant domesticated in tropical countries, *C. esculenta*, to naturally attenuate the impact of diuron, an herbicide widely used in the intensive agriculture. The first point of this perspectives article is to demonstrate the capacity of *C. esculenta* to perform the rhizofiltration of diuron on lab-scale. The second point is to study the compatibility of *C. esculenta* for curbing diuron pollution while keeping its traditional food use intact. The choice of initial diuron concentration is an important consideration. Many works are described at concentrations higher than those that can be found in a natural environment. This choice is frequently guided by the lack of analytical precision of the implemented methods. However, several measurements of diuron concentration *in natura* were reported, such as 3.05 µg.L⁻¹ in Japan (Okamura et al., 2003), from 0.2 to 3 µg.L⁻¹ in Australia (Anzecc and Armcanz, 2000) and 0.43 µg.L⁻¹ in Europe (Lamoree et al., 2002). The variability of diuron concentration in water which depend of the season and drought episodes (Skerratt et al., 2023), makes us to deliberately chose a concentration below the values described in the literature. The rhizofiltration experiments were thus performed on synthetic solutions containing diuron at initial concentration of 0.1 µg.L⁻¹.

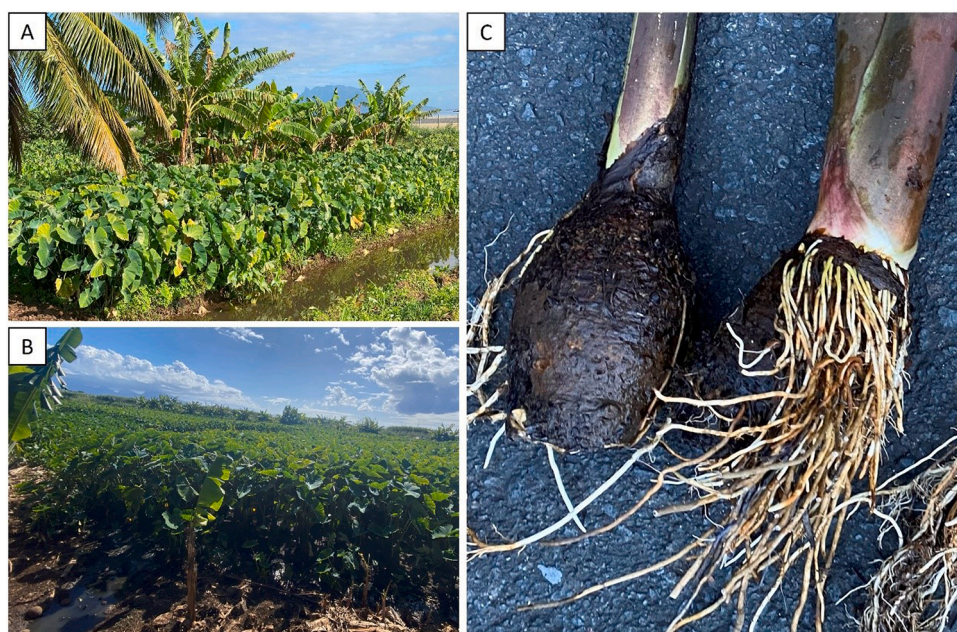


Fig. 1. A&B: French Polynesian *C. esculenta* plantations irrigated by fresh water. C: *C. esculenta* corms and their root systems. Credit @Annaïg Le Guen / Criobe / CNRS.

2. Materials and methods

2.1. Materials

Buckets and breeding ground from the Verve company were bought in Castorama shop. 0.22 μm syringe-filters were purchased from the Phenomenex company. The samples were crushed by a Waring Commercial blender equipped with a 2 L bowl. The rhizofiltration experiments used tap water. Acetone, water and methanol used for HPLC analyses were purchased from Carlo Erba company. Diuron was purchased from TCI company. Diuron- d_6 was purchased from LGC-standards company.

HPLC-UV-Vis analyses were performed on a Waters Alliance Waters Alliance e2695 coupled with a Waters photo diode array detector 2998.

UPLC-TQMS analyses were performed on a Shimadzu Nexera X2 equipped with a LCMS-8050 triple quadrupole detector.

2.2. HPLC-UV-Vis for rhizofiltration experiments

The experimental data for this apparatus were reported on the Electronic supporting information.

2.3. UPLC-TQMS for the separation of *C. esculenta* parts

The experimental data for this apparatus were reported on the Electronic supporting information.

2.4. Study of *C. esculenta* capacity for the rhizofiltration of diuron

2.4.1. *C. esculenta* plants management

C. esculenta plants were collected in the area of Moorea, French Polynesia. Each *C. esculenta* plant was placed in a bucket filled with breeding ground at least up to the tuber height and were daily thoroughly watered until they were used (At least 3 weeks). Before rhizofiltration experiments, each *C. esculenta* plant was carefully removed from its bucket while keeping the root system intact. Each plant was washed with tap water until all the breeding ground was removed.

2.4.2. Rhizofiltration experiments

Six 15 L plastic crates were equipped with a magnetic stirrer and filled with 10 L of tap water. In crates A, B and C (3 replicates) were added 4.63 mL of a diuron solution at 216 mg.L^{-1} in propan-2-ol in order to obtain a diuron concentration at 100 $\mu\text{g.L}^{-1}$. Crates D, E and F acted as 3 control experiments and were filled with 10 L of tap water. The six solutions were stirred for one hour to get perfectly homogeneous solutions. Initial samples at $t = 0$ min (1 mL) were collected and filtered with a 0.22 μm syringe-filter. While stirring, 1 freshly washed *C. esculenta* plant was added in each crates ensuring that all the root system and the tuber were well immersed (Fig. 2). 1 mL samples of each solution were collected after 2, 4, 6, 24, 48 and 72 h Each sample was filtered under 0.22 μm and stored at 5 $^{\circ}\text{C}$ before analysis.

Aside, a 1 L becker-type flask equipped with a magnetic stirrer was filled with 1 L of tap water. 0.463 mL of a solution of diuron at 216 mg.L^{-1} in propan-2-ol were added and the solution was stirred at room temperature. 1 mL samples of the solution were collected at 0, 2, 4, 6, 24, 48 and 72 h After 72 h of stirring, the final volume was measured in order to quantify the water evaporated during the rhizofiltration experiments time.

2.5. Effect of diuron rhizofiltration on the *C. esculenta* edibility: *C. esculenta* tuber treatment process

The treatment steps were inspired from the standard procedure (AFNOR, 2013). The different steps were represented in Fig. 3 and were detailed further in the text.

2.5.1. Separation heart/peel and roots

After 72 h stirring, each plant was removed from its crate. The aerial part was removed and the root system and the peel were separated from the heart of the tuber with a knife and placed into 2 distinguished crystallizers. The resulting 12 crystallizers were weighted, dried in an oven at 40 $^{\circ}\text{C}$ for 44 days and were then weighted again. The different masses were reported in the Electronical Supporting Information (Table 6).

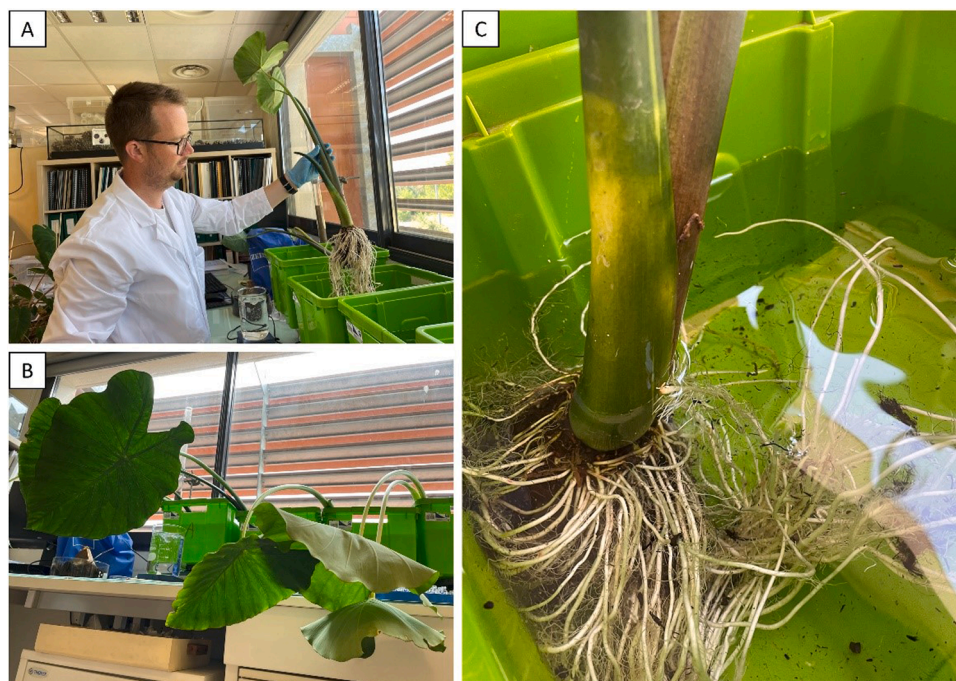


Fig. 2. Setting rhizofiltration experiments. A&B: Putting a washed plant of *C. esculenta* into the crate. C: *C. esculenta* root system bathed into a diuron solution containing crate. Credit @Claude Grison, CNRS.

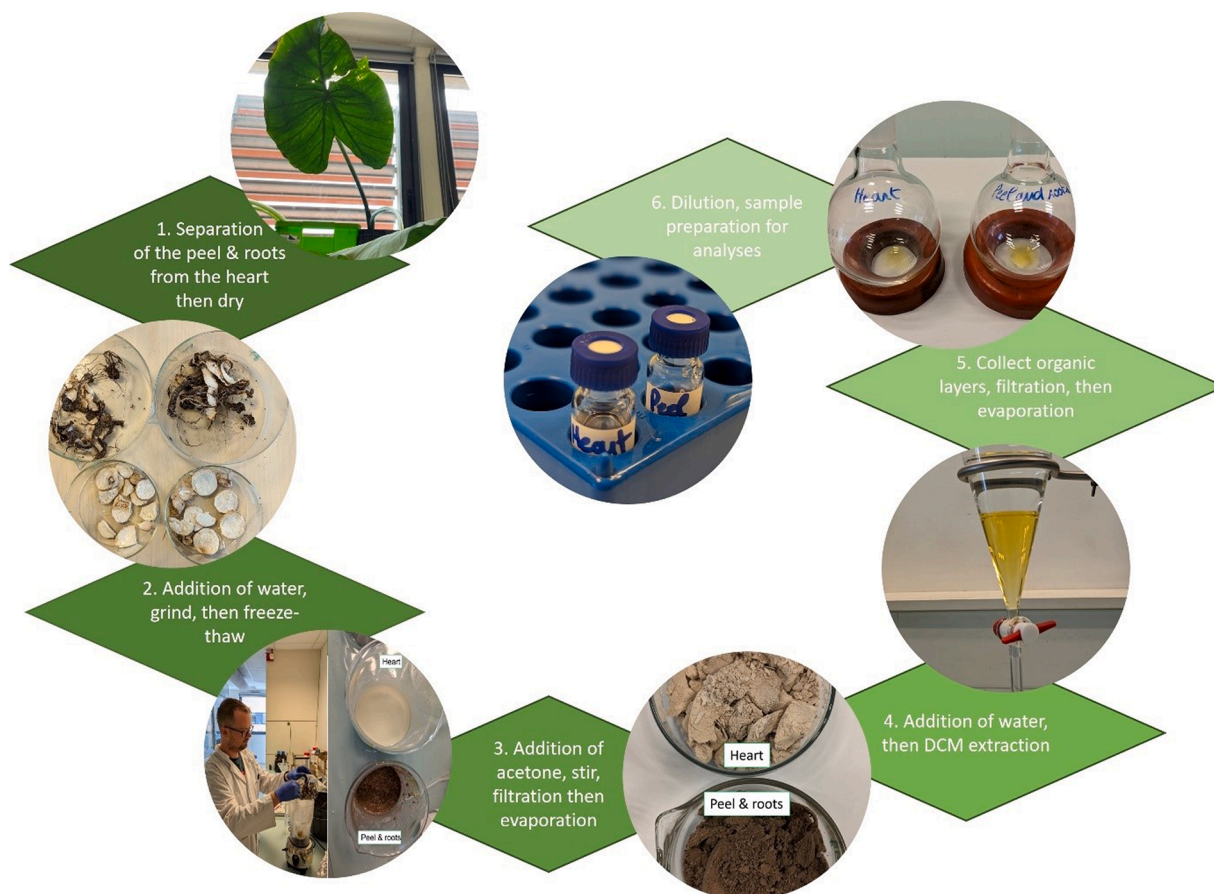


Fig. 3. Representation of the treatment steps. Credit @P-A Deyris, University of Montpellier.

2.5.2. Grinding samples

Each of the dried solids obtained in the previous step was transferred into a blender followed by a certain volume of water (reported on Table 6 of the Electronical Supporting Information). Each mixture was grinded by using 3 times the following steps: 1 min at high speed then 1 min of rest. The final volumes (water + H or PR) were reported on the Electronical Supporting Information (Table 6). The homogeneous mixture was transferred into a 500 mL Eppendorf-type flask.

2.5.3. Freezing-thawing cycles

Freeze-thaw cycles (liquid nitrogen at $-196\text{ }^{\circ}\text{C}$ until complete freeze then $40\text{ }^{\circ}\text{C}$ water bath until complete thaw) were performed in order to break membranes of the cells. Optical microscopy analyses were performed with Trypan blue as control. It has been established that 7 cycles were enough to break more than 95 % of the cell's membranes in heart mixtures while it required 10 cycles for the peels and roots mixtures to obtain the same ratio.

2.5.4. Biopolymer's precipitation

A certain volume of acetone was added to each mixture (the Electronical Supporting Information, Table 6) in order to precipitate some of the biopolymers and to help the solubilisation of small organic molecules. (AFNOR, 2013) At the same time, 0.333 mL of a diuron- d_6 solution ($30\text{ mg}\cdot\text{L}^{-1}$ in propan-2-ol, 10 ng) were added to the mixture. Diuron- d_6 acted as an internal standard. The mixture was stirred for 1 h and was then filtered on a Büchner-type filter equipped with a cellulose filter. The resulting solid was washed with 100 mL of acetone and then filtered. The filtrate was evaporated under reduced pressure and the mass of the solid was weighted and reported on the Electronical Supporting Information (Table 6).

2.5.5. Extraction process

150 mL of water were added into each flask and the solid was put into an ultrasonic bath in order to obtain a homogeneous suspension. 20 mL of this suspension were transferred into a separating funnel. The mixture was extracted with $3 \times 20\text{ mL}$ of dichloromethane. The organic layers were combined, dried over MgSO_4 , filtered through a cellulose filter and then evaporated under vacuum. This provided a translucent yellow solid. Several extraction experiments with two other solvents were realised (Ethyl acetate and diethyl ether) but dichloromethane (DCM) showed an ability to totally extract diuron while solubilise the less of matrix compounds. Ethyl acetate and diethyl ether which are more polar than DCM, solubilised too much matrix and make HPLC analyses less easy to perform (overpressure of the apparatus).

2.5.6. HPLC samples preparation

The yellow solid was first dissolved in 10 mL of HPLC grade MeOH, then 10 mL of HPLC grade water were added. A white precipitate, which was assessed not to be diuron or diuron- d_6 , was filtered through $0.45\text{ }\mu\text{m}$. The resulting solution was transferred into a HPLC vial and then analysed.

3. Results

3.1. Laboratory study of *C. esculenta* capacity for the rhizofiltration of diuron

The rhizofiltration experiments were conducted in triplicates (Rhizo A, B and C) for 72 h of contact time between the *C. esculenta* plant and the diuron aqueous solution (See Material and Methods, part 2.4). Samples were collected and analysed at different times in order to monitor the evolution of diuron concentration in the crates. The values

were reported on Table 1, entry 1. These results show a decrease in diuron concentration while increase in contact time for Rhizo B and C. However, the diuron concentration for Rhizo A appears to stagnate and the values increase for 48 and 72 h at 88.1 and 88.4 $\mu\text{g}\cdot\text{L}^{-1}$ respectively. During the 72 h of contact time, a part of the water contained in the crates evaporated and needed to be quantified in order to be able to correct the observed diuron concentration. The water evaporation rate was calculated and were reported in Table 1, entry 2. The corrected concentration values were calculated and their values were reported in Table 1, entry 3. For the 3 rhizofiltration experiments, the values decreased slowly up to 66.4 $\mu\text{g}\cdot\text{L}^{-1}$ for Rhizo C. The corrected values in hands, the rhizofiltration yields were calculated for each experiment at different times (Table 1, entry 4) as well as the average yield (Table 1, entry 5). The experiments Rhizo B and C indicate very close results at respectively 27.4 % and 27.8 % while Rhizo A yield was calculated at only 15.2 %. These results show that the average rhizofiltration yield on triplicate experiments at 72 h could reach 23.5 % \pm 5.5 %.

3.2. Effect of diuron rhizofiltration on the *C. esculenta* edibility

The treatment was realised on the 3 *C. esculenta* stemmed from the rhizofiltration experiments (Rhizo A, B and C) so as on the *C. esculenta* from the 3 control experiments (See Material and methods part 2.5). The resulting concentrations of each sample after extraction were reported in Table 2. Calculations were also realised in order to obtain the final concentration of diuron in each fresh *C. esculenta* part (Heart and Peel&Roots). The first observation is that all the concentrations of the control experiments (Table 2 Control 1 to 3) were around or lower than 1 $\mu\text{g}\cdot\text{kg}^{-1}$, which is around the LoD of the UPLC detector. These results confirmed the initial observation made during the rhizofiltration experiments that the *C. esculenta* plants were not contaminated by diuron. The second observation is that there is a really huge difference of diuron concentration between the heart (H) and the Peel and the Roots (P&R) for the three rhizofiltration experiments (Table 2, Rhizo A, B and C). H contained 9, 6 and 4 μg of diuron per kg while the P&R contained respectively 1833, 1839 and 1145 $\mu\text{g}\cdot\text{kg}^{-1}$. By the calculation of the partition ratio between the heart and the peel & roots parts, only 0.3 to 0.8 % of the total rhizofiltrated diuron migrate to the heart. This means that the rhizofiltrated diuron stays sequestered in the peel and the roots and barely migrate to the heart.

4. Discussion

The results showed a slow but continuous uptake of diuron by *C. esculenta*, which reached 23.5 % \pm 5.5 % in 72 h of rhizofiltration. *C. esculenta* are able to naturally sequester diuron in their root system. If

the phenomenon is slow, it is compatible with the establishment of *C. esculenta* plantations, which could last up to 40 weeks. This result could be advantageously compared to data described in the literature. One example related a method of phytoremediation applied to diuron removal. Authors used 6 plant species (*Canavalia ensiformes* (L.) DC., *Stilzobium aterrimum* L., *Raphanus sativus* L., *Crotalaria spectabilis* Roth, *Lupinus albus* L., and *Pennisetum glaucum* (L.)) in phytoextraction experiments on ^{14}C -diuron contaminated soils. The best result was obtained with *Stilzobium aterrimum* L. which could phytoextract 7.82 % \pm 2.72 of diuron (Teófilo et al., 2020). The method of rhizofiltration presented in our work which showed better result, highlighted that *C. esculenta* could provide a new ecosystem service through the slow and progressive sequestration of toxic and ecotoxic organic pollutants for aquatic life.

These encouraging results with *C. esculenta* raised the question of the mechanism of diuron sequestration and the role of the plant species in the rhizofiltration phenomenon. In this presented work, the fact that the diuron is not internalised in the heart of the corm, but still present on its surface, led us to think that the process is more physicochemical than biological. We hypothesize that the diuron stays adsorbed at the root level. This hypothesis is supported by the work of De Laet et al. (De Laet et al., 2019). In this article, the living plant *Eichhornia crassipes* showed to be able to phytoaccumulate several organic pollutants. The same plant whose roots were reduced into powder showed the same results on the adsorption of organic pollutants. These results were strengthened by another article relating the biosorption of pesticides and solar filters. (Deyris et al., 2023). This hypothesis is supported by a biosorption experiment using ground *C. esculenta* roots in contact with an aqueous solution of diuron (See Electronic Supplementary Information part 4.). The average of three replicates leads to 12.1 % \pm 0.1 % biosorption after 15 h of agitation. This result is very close to the rhizofiltration performance of *C. esculenta* under the same conditions. It is therefore likely that the rhizofiltration mechanism is based on an adsorption phenomenon on the surface of the roots (See Electronic Supporting Information part 4.).

These first data raise another question regarding the edibility of *C. esculenta* grown in a polluted environment. Indeed, in many Pacific islands, *C. esculenta* is an essential element of traditional family meals or daily meals as a source of slow carbohydrates (Lebot and Ivančić, 2022). Considering this, it is legitimate to ask whether the ability of *C. esculenta* to phytoaccumulate diuron is an opportunity to mitigate the impact of this pesticide on ecosystems but a risk of contamination of the food chain. Regarding the results obtained after treatment of the roots, peel and heart of *C. esculenta* (Table 2), the diuron concentrations in the heart do not exceed 9 $\mu\text{g}\cdot\text{kg}^{-1}$ (replicate Rhizo A), while those in the peel and roots vary between 1145 and 1833 $\mu\text{g}\cdot\text{kg}^{-1}$. The partitioning rate of

Table 1
Diuron rhizofiltration experiments (Rhizo A, B and C) monitoring and calculations.

Entry	Time		0	2	4	6	24	48	72
1	Observed diuron concentration ($\mu\text{g}\cdot\text{L}^{-1}$)	Rhizo A	90.6 \pm 2.4	90.2 \pm 2.4	89.1 \pm 2.4	88.7 \pm 2.4	87.9 \pm 2.4	88.1 \pm 2.4	88.4 \pm 2.4
		Rhizo B	90.4 \pm 2.4	86.2 \pm 2.3	85.5 \pm 2.3	84.2 \pm 2.3	80.6 \pm 2.2	77.0 \pm 2.1	75.5 \pm 2.0
		Rhizo C	91.8 \pm 2.5	86.5 \pm 2.3	86.6 \pm 2.3	84.7 \pm 2.3	81.5 \pm 2.2	78.0 \pm 2.1	76.4 \pm 2.1
2	Water evaporation rate		0.00 %	0.75 %	0.94 %	1.12 %	4.56 %	8.27 %	13.12 %
3	Corrected diuron concentration ($\mu\text{g}\cdot\text{L}^{-1}$)	Rhizo A	90.6 \pm 2.9	89.5 \pm 2.9	88.3 \pm 2.8	87.7 \pm 2.8	83.9 \pm 2.7	80.8 \pm 2.6	76.8 \pm 2.5
		Rhizo B	90.4 \pm 2.9	85.5 \pm 2.7	84.7 \pm 2.7	83.3 \pm 2.7	76.9 \pm 2.5	70.7 \pm 2.3	65.6 \pm 2.1
		Rhizo C	91.8 \pm 2.9	85.8 \pm 2.7	85.7 \pm 2.7	83.8 \pm 2.7	77.7 \pm 2.5	71.6 \pm 2.3	66.4 \pm 2.1
4	Rhizofiltration yield	Rhizo A	0.0 %	1.2 %	2.6 %	3.1 %	7.4 %	10.8 %	15.2 %
		Rhizo B	0.0 %	5.4 %	6.3 %	7.8 %	14.9 %	21.8 %	27.4 %
		Rhizo C	0.0 %	6.6 %	6.6 %	8.8 %	15.3 %	22.1 %	27.8 %
5	Average yield		0.0 %	4.4 % \pm 2.1 %	5.2 % \pm 1.7 %	6.6 % \pm 2.3 %	12.5 % \pm 3.4 %	18.2 % \pm 4.9 %	23.5 % \pm 5.5 %

Table 2Diuron concentrations in the different *C. esculenta* parts after treatment. H = Heart. P&R = Peel and Roots.

Sample		Diuron concentration after extraction ($\mu\text{g.L}^{-1}$)	Diuron mass after precipitation step (μg)	<i>C. esculenta</i> parts fresh masses (g)	Diuron concentration in each <i>C. esculenta</i> part ($\mu\text{g.kg}^{-1}$)	Diuron partition ratio H / P&R
Control 1	H	0.90 ± 0.12	0.14	140.38	< 1	–
	P&R	1.51 ± 0.20	0.23	154.25	1	
Control 2	H	0.37 ± 0.05	0.06	198.97	0	–
	P&R	1.18 ± 0.15	0.18	109.08	2	
Control 3	H	0.25 ± 0.03	0.04	429.69	0	–
	P&R	0.91 ± 0.12	0.14	177.58	1	
Rhizo A	H	4.98 ± 0.65	0.75	82.55	9	0.8 / 99.2
	P&R	623.07 ± 81.00	93.46	51.00	1833	
Rhizo B	H	7.76 ± 1.00	1.16	187.72	6	0.6 / 99.4
	P&R	1320.83 ± 171.71	198.12	107.75	1839	
Rhizo C	H	4.13 ± 0.54	0.62	584.03	4	0.3 / 99.7
	P&R	1381.41 ± 179.41	207.21	181.00	1145	

diuron ranges from 0.3/99.7 for replicate Rhizo C to 0.8/99.2 for replicate Rhizo A. These data confirm that most of the diuron is sequestered in the peel and roots and does not migrate to the heart. According to European standards (European parliament, 2023), the maximum concentration of pollutants in fresh foods should not exceed $10 \mu\text{g.kg}^{-1}$. The values obtained in laboratory experiments are below the standards. After careful peeling of the corm, the heart of *C. esculenta* plants should therefore be edible. On a practical level, some recommendations should be followed to avoid the spread or diffusion of diuron. It is highly recommended to wash the heart thoroughly with water and to separate the P&R from other compostable organic waste. If the use of the roots of this species for remediation purposes does not call into question this nutritional value, it must be accompanied by explanations and recommendations to ensure good management of the contaminated parts (roots and peel of the corms). It is therefore necessary to integrate this dimension of information with the populations and to structure the management of contaminated waste by the public authorities in order to transform a phytotechnology into a socio-ecological advantage. This could lead to the creation of a new compost sector which is specialised in contaminated biomass. Moreover, it could be interesting to promote a reciprocity of knowledge between the older generations who know the nutritional and culinary virtues of *C. esculenta*, and the younger generations who would be made aware of the challenges of phytoremediation and the associated precautions.

A comparative study with the different diuron treatment methods described in the literature was carried out. Two parameters were considered: the environmental aspect and the socioeconomic dimension of each technology. Beyond the aforementioned and ineffective phytoextraction attempts (Teófilo et al., 2020), other strategies have been described. These technologies can be grouped into three categories: adsorption (Carvalho et al., 2022; Xiang et al., 2020), filtration (Ma et al., 2024) and degradation (Xie et al., 2024) and were summarized in Table 3. It is undeniable that each category possesses assets providing an

interesting efficiency for the removal of herbicide, which is already well-documented and will not be discussed in this paper. However, most of these methods do not take into account other relevant parameters such as the environmental footprint, the economic cost and the large-scale feasibility. In the field of adsorption, biochar and activated carbon are the most described adsorbents over the last decade. The use of raw materials originated from biomasses, sludges or agricultural wastes falls within the criteria of sustainability. However, the production steps (pre-treatment, thermal processing and post-treatment) involve a huge energy consumption and a problematic use of chemicals (Xiang et al., 2020). Moreover, the quality of initial biomass is essential to produce efficient biochar and to limit the production of toxic gas during the pyrolysis. Therefore, not all available biomasses are necessarily relevant (Carvalho et al., 2022). Concerning the recycling of biochar (solvents extraction, calcination), these treatment methodologies still have a strong environmental impact (Yang et al., 2020). Filtration techniques frequently use ceramic membranes which remain expensive and delicate to set up (He et al., 2019). They require the use (and therefore the preparation) of metal oxides, high temperatures, various petro-sourced additives (binders, plasticizers), organic solvents, strong acids, or organic ligands (Hubadillah et al., 2022). Currently, ceramic membranes remain confined to the laboratory scale (Asif and Zhang, 2021). Degradation techniques are mainly based on oxidative methods (Yang et al., 2024) and thus on the use of powerful, even problematic, oxidants (Miklos et al., 2018; Mohd Ghazi et al., 2023). Moreover, they generate degradation products which can be as toxic as the initial pollutant (Katsumata et al., 2009).

One of the major advantages of the proposed methodology is based on the large-scale cultivation capacities and local know-how that are already acquired. This concerns a large geographical area, because *C. esculenta* is already one of the first domesticated species in Asia and the Pacific. In addition, the plant species is appreciated in Polynesia and Melanesia for its high productivity despite the high rainfall in these

Table 3

Summary of the advantages and the disadvantages of the different methods for removing diuron from water.

Method	Environmental aspects		Social and economic aspects	
	Advantages	Disadvantages	Advantages	Disadvantages
Adsorption	- Waste biomass as raw materials	- Difficult recycling - Huge energy consumption - Use of chemical reagents	- Waste biomass as raw materials - Usable at large scale	- Long time process to obtain efficient biochar - Dependent of initial quality of biomass
Filtration	- Small size technology	- Expensive and delicate preparation of filters - Use of huge amounts of chemicals during preparation	- Coupling with degradation catalysts to enhance efficiency	- The technology is still at lab-scale
Pollutant degradation	- Small amount of catalysts - UV treatment	- Use of problematic oxidants - Degradation products more toxic than initial pollutant	- Efficient recycling of the catalysts	- Contamination of local environment by degradation products
Rhizofiltration with <i>C. esculenta</i>	- Available around the world	- Lack of specific treatment sector	- Selective pollutant sequestration - Cheap	- Local population may have food trust issues

territories. As such, the phytotechnology of capturing diuron by this species is therefore a major advantage for its large-scale deployment. In a context of ecological transition, the intensification of *C. esculenta* cultivation may present another advantage. T. Bambridge notably showed that *C. esculenta* has a good sediment retention capacity in a context of intensive diuron cultivation which tends to erode soils (Bambridge et al., 2017). Our work demonstrated that the capacity of *C. esculenta* to mitigate the impact of diuron is compatible with its traditional food use. Compatibility of uses is an important point, which allows to reconcile protection of the environment and people, and agricultural interest. This situation permits to limit conflicts of use and interest and therefore to facilitate the acceptance of the technology. *C. esculenta* is thus a species of choice to respond to several ecological and socio-economic issues. This plant species therefore allows to provide relevant solutions in terms of sustainable development.

5. Conclusion

Here we report the feasibility of a natural solution to protect aquatic ecosystems from the herbicide diuron currently used in our many food crops in Southeast Asia and the Pacific Islands. The plant *C. esculenta*, which is part of common crops, naturally phytoaccumulates the herbicide diuron up to 24 % after 72 h of exposure. This study was carried out by deliberately placing itself below the known levels of diuron in the environment to truly test the potential of the proposed solution, but with excellent analytical precision. Given the food use of *C. esculenta* tubers, the issue of edibility was also studied and <1 % of the pollutant migrated into the heart part which is still edible according to European standards. Diuron-contaminated water from intensive agricultural activities such as pineapple or sugarcane plantations could be used to irrigate *C. esculenta* plantations without jeopardizing the edibility of the tubers. Diuron is believed to be phytoaccumulated by *C. esculenta* plants and the resulting water, which contains less diuron, could be released into the environment. For customers and farmers, precautions should be taken, as the diuron level in the skin and roots is high. These parts of the *C. esculenta* must be treated separately from the usual compostable biomasses. It is therefore a new local management that must be rethought in this sense.

According to the results presented, *C. esculenta* could act as a rhizofiltration agent for other biocides. Since the rhizofiltration capacity depends on the solubility of the pollutant (Deyris et al., 2023), this method could be applied to persistent and emerging organic pollutants that have a solubility close to that of diuron, such as chlorinated insecticides, other herbicides such as ametryn, or organic UV filters.

The proposed solution therefore makes it possible to reduce environmental pollution caused by diuron, while preserving the food use of the plant and therefore human health.

These results, still at the proof-of-concept stage, are very encouraging. A large-scale transposition, *in natura*, could be used to solve pollution problems related to the management of the land-sea continuum. It revealed a new ecosystem service of *C. esculenta* and is part of a promising approach to socio-ecological transition.

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CRedit authorship contribution statement

Pierre-Alexandre Deyris: Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Franck Pelissier:** Resources, Formal analysis, Data curation. **Claire M. Grison:** Resources, Methodology, Investigation, Data curation. **Claude Grison:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2024.100583.

Data availability

Data will be made available on request.

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