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Sustainable Agricultural Practices for Managing Rice Crops to Minimize Environmental Contamination from the Pesticide Imazamox

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Abstract

Weed management is crucial for the sustainable production of rice (*Oryza sativa* L.), although herbicides such as Imazamox (IZX) can persist in soils, posing risks to soils and water resources. This two-year study evaluated the effects of soil physicochemical properties under different irrigation and tillage practices, with and without compost derived from olive mill waste, on IZX behavior. The treatments implemented were as follows: no-tillage and sprinkler (NT-S), conventional tillage and sprinkler (T-S), conventional tillage and flooding (T-F), and the corresponding regimes with compost amendment (NT-SC, T-SC, and T-FC). Sorption–desorption, dissipation, and leaching of the herbicide were assessed. The IZX adsorption was lower under soil collected from sprinkler irrigation, especially in NT-S, while compost reduced the adsorption under T-SC and T-FC. Dissipation was faster in NT-S and T-S soils, in which the half-life of IZX declined up to 30% relative to T-F. Furthermore, compost further accelerated herbicide dissipation, correlating with higher organic carbon content and microbial activity. The IZX losses via leaching were significantly reduced in soils irrigated by sprinkler in combination with compost, with values $\leq$ 48.5% of the IZX applied. These results indicate that the irrigation regime and organic amendment strongly influence soil physicochemical properties, then influencing the environmental fate of IZX. Integrated management using sprinkler irrigation and compost can mitigate IZX persistence and leaching, improve soil health, and reduce the risk of water contamination, representing a sustainable strategy for rice cultivation.

Keywords: environmental protection; organic amendment; sorption; leaching; Imidazolinone

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1. Introduction

Rice (*Oryza sativa* L.) constitutes a primary food source for a large proportion of the global population; however, weed infestation can severely compromise its production, leading to substantial yield reductions and threatening its sustainability [1]. Consequently, effective weed management, in which the application of herbicides plays a key role, is a critical component of rice production systems [2,3]. Nevertheless, a considerable fraction of the applied herbicide does not reach the intended target and may persist in soils or migrate to surface and groundwater bodies, posing environmental risks. Moreover, conventional rice farming relies on agronomically unsustainable practices, such as intensive soil tillage and continuous flooding irrigation [4], which are closely linked to soil degradation [5] and high water demand [6]. In this context, the adoption of sustainable and innovative agricultural strategies for rice cultivation has become increasingly necessary [7–9].

Several water-efficient irrigation strategies have been explored in rice cultivation, including aerobic rice systems, alternate wetting and drying, drip irrigation, and sprinkler irrigation. Among these approaches, sprinkler irrigation has been increasingly promoted as a viable alternative to conventional flooded rice systems, as it substantially enhances water use efficiency, achieving reductions of up to 70% in irrigation water requirements along with significant improvements in water productivity [10,11]. Beyond conserving water, sprinkler irrigation also supports soil conservation practices, including direct seeding and the application of organic amendments [12]. Given the deterioration in the soil physical and chemical properties associated with intensive tillage in rice farming [13], conservation strategies—particularly no-tillage systems—are especially important for soils that typically have low organic matter content [14]. Long-term adoption of these practices has been shown to significantly increase soil organic matter levels [15,16]. Despite these advantages, rice producers may be hesitant to adopt water-saving irrigation methods due to the potential risk of yield losses [17], as yield reductions have been frequently reported under sprinkler irrigation systems, regardless of the tillage regime, particularly in soils with low organic matter content (<25 g kg^{-1}) [18,19]. In this regard, the combined application of sprinkler irrigation and organic amendments, such as compost, has a substantial positive impact by improving the soil properties and water retention capacity, thereby supporting optimal crop development and increasing yields [20,21], making this approach an efficient and sustainable alternative to conventional flooded rice systems.

Olive oil production represents an important socioeconomic activity in the Mediterranean region, generating substantial amounts of byproducts in the form of a semi-solid residue, commonly referred to as "alperujo" in Spanish. When this residue is improperly disposed of in soils, it can exert pronounced phytotoxic and antimicrobial effects and contribute to increased soil salinity and nitrogen immobilization [22]. Nevertheless, given its high organic matter content (>84%), alperujo can be transformed into a valuable organic amendment through composting [23]. The application of this amendment, together with conservation practices such as sprinkler irrigation and no-tillage, significantly modifies the soil physicochemical and biological characteristics that are critical in determining the fate, persistence, and mobility of herbicides in soils [24,25]. Therefore, understanding how these management practices influence soil properties and, consequently, herbicide behavior is essential, particularly for commonly used compounds such as Imazamox.

Imazamox (IZX), chemically identified as 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid, is widely used for the control of annual and perennial grass and broadleaf weed species in rice cropping systems based on Imidazolinone-resistant cultivars [26]. However, the available scientific literature on the influence of different agricultural management practices, including the application of organic amendments, on the environmental fate of IZX is limited and even contradictory. Previous studies have indicated that the use of biochar as a soil amendment decreased the soil sorption capacity of IZX [27] and reduced the persistence and leaching of IZX [28]. In contrast, Dechene et al. [29] reported that biochar had no effect on either the sorption or leaching of IZX. Further, Kaur et al. [30] showed that a biocomposited amendment increased the IZX dissipation rates in different soil types. Moreover, to the best of our knowledge, no published studies have evaluated the effects of different agricultural practices for rice production combined with olive-mill-waste compost application on IZX behavior. This approach could represent a sustainable and economically viable alternative to other amendments, such as biochar, while also contributing to one of the fundamental objectives of the European Union's Circular Economy Strategy: waste reuse [31]. Studies conducted with other herbicides have shown that olive-mill-waste compost applications can reduce herbicide persistence [32,33] and leaching [34], although these behaviors may be affected by the properties of the pesticide, crop management system, and the degree of organic amendment evolution [34,35]. Therefore, to support decision-making by rice growers and improve the sustainability of cropping systems, there is a clear need for studies that validate and integrate existing findings on the behaviors of IZX under different agricultural management practices in combination with compost amendment.

Accordingly, the main objective of the present study was to evaluate the effects of soil physicochemical properties under different irrigation and tillage practices, with and without compost application, on the behavior of IZX in rice soils. To achieve this objective, the processes of sorption–desorption, dissipation, and leaching of the herbicide were investigated under laboratory conditions. The results obtained are expected to support the efficient planning of IZX use and promote sustainable alternatives for rice cropping systems.

2. Materials and Methods

2.1. Field Study Design and Soil Characterization

A field experiment was conducted over two consecutive years (2018 and 2019) in a rice (*Oryza sativa* L.) field site in southwest Spain (38°55′ N, 6°57′ W) (Figure 1a). The main climatic characteristics recorded during the growing seasons are presented in Figure S1. The site had been under continuous rice monoculture for 14 years and was managed using conventional practices, including flooding and tillage. The experimental area presents a soil classified as loam, whose distribution of particle size was 50.3% sand, 28.9% silt, and 20.8% clay. The experimental area was divided into 18 plots, each measuring 180 m^2, arranged randomly across the field. Six treatments were applied, each with three replicates: no-tillage and sprinkler irrigation (NT-S), conventional tillage and sprinkler irrigation (T-S), conventional tillage and flooding irrigation (T-F, which is the common management practice, control), and the corresponding regimes with compost amendment (NT-SC, T-SC, and T-FC) (Figure 1b). These treatments were selected to reduce water consumption and improve the soil quality. The compost, derived from olive oil production waste, had a total organic carbon content of 382 g kg^{-1} and a pH of 7.7. According to a previous study [36], to prevent rice yield reduction under sprinkler irrigation, the compost was applied at a rate of 80 Mg ha^{-1} in a single application throughout the study before sowing (April). The compost was manually spread over the soil surface and then incorporated to a depth of approximately 0–20 cm using a disc harrow. All experimental plots received the same fertilization program in both years. Before sowing, 550 kg ha^{-1} of a 9-18-27 compound fertilizer (Fertiberia, Madrid, Spain) was applied as basal fertilization. Nitrogen was subsequently supplied as urea (Fertiberia, Madrid, Spain) in two split doses: 92 kg ha^{-1} at tillering and 69 kg ha^{-1} at panicle initiation. The rice cultivar 'Sirio' (COPSEMAR, Madrid, Spain) was sown in all treatments at a rate of 160 kg ha^{-1}. Weed control in the field plots was carried out using herbicides other than Imazamox (IZX), which was not applied at any time prior to soil collection. For plots under sprinkler irrigation, a Semeato TDNG 320-disc seeder (Semeato, Passo Fundo, Brazil) was used, while an Amazone ZA-X Perfect broadcast seeder (Amazone, Munich, Germany) was employed for flooded plots. To evaluate the effects of the different management systems on the environmental fate of IZX, soil samples were collected immediately after the rice harvests, which took place at the end of September 2018 and 2019. Thus, for each plot, four random topsoil subsamples (0–20 cm) were collected using a 70 mm manual auger and combined to form a composite sample. The samples were then air-dried, gently crushed, and sieved to <2 mm, and the fine fraction was stored at 4 °C until further analysis. The soil properties were analyzed following the methods described by Peña et al. [37], and the results are summarized in Table S1. The collected soil samples were subsequently used to conduct the IZX sorption–desorption, dissipation, and leaching experiments (Figure S2).

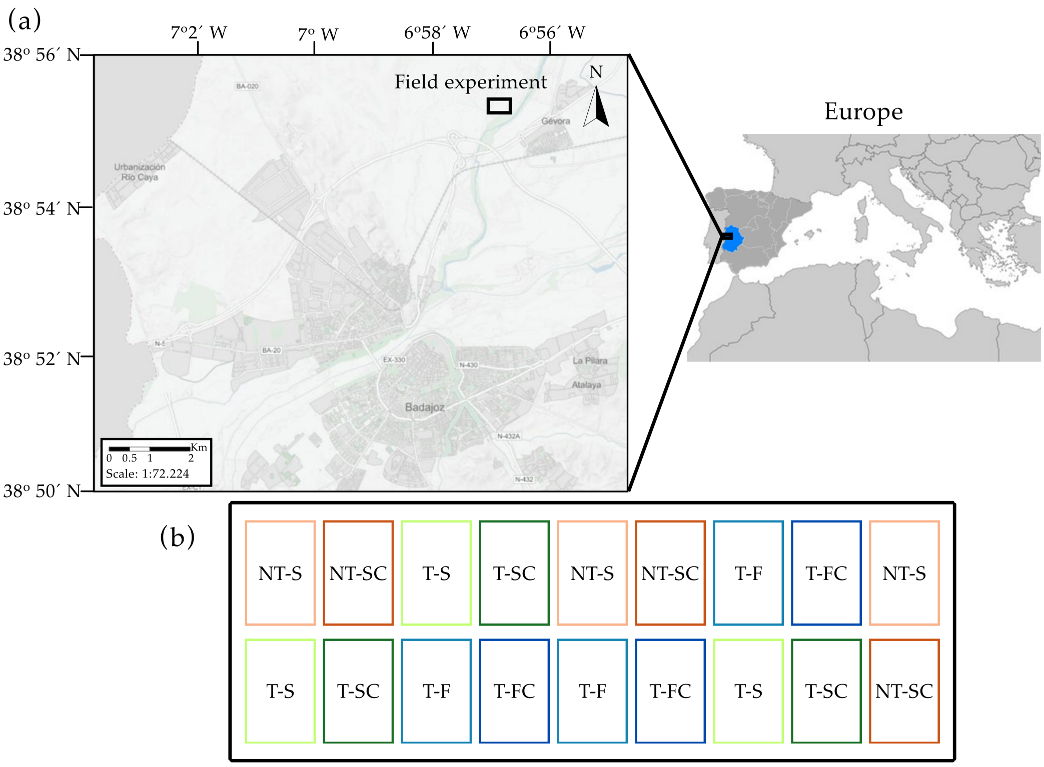

Figure 1. Study area and experimental design of rice cultivation: (**a**) geographical location of the rice growing area (adapted from the National Geographic Institute of Spain; retrieved from: https://signa.ign.es/signa/ (accessed on 8 January 2026); (**b**) layout of the experimental plots.

2.2. Adsorption and Desorption Experiments

Adsorption–desorption isotherms of IZX were determined in triplicate for both compost-amended and unamended soils using the batch equilibration technique. The Freundlich model was applied to fit the IZX adsorption–desorption data. The IZX adsorption and desorption experiments were fitted to the empirical Freundlich equation, $C_s = K_f \, C_e \, (1/n_f)$, where Cs ($\mu$M kg^{-1}) is the amount of herbicide sorbed at the equilibrium concentration C_e (μM L^{-1}), and K_f and nf are constants that characterize the relative sorption capacity. Distribution coefficients (K_d) were obtained from the sorption isotherms according to $K_d = C_s/C_e$, using a selected C_e of 2.5 μM. The desorption percentage was calculated as $\% \, D = ((C_{sa} - Csd)/C_{sa}) \times 100$, where C_{sa} is the amount of IZX adsorbed during the sorption phase and C_{sd} is the amount of IZX adsorbed in desorption process. Additional methodological details are provided in the Supplementary Materials (Text S1).

2.3. Dissipation Experiments

Considering previous reports indicating that IZX remains stable under flooded (anaerobic) conditions [38], dissipation experiments were conducted exclusively under non-flooded (aerobic) incubation conditions for soils from all treatments. IZX was applied at a concentration of 2.2 μg g^{-1}. For residue analysis, soil samples from each treatment were collected in triplicate at regular intervals over a 0–70 day period following application. IZX was extracted from the samples, and concentrations in the supernatant were quantified using HPLC. Thus, the soils (5 g) were extracted by 8 mL of a 80:20 (*v*/*v*) diluted H_3PO_4/acetonitrile mixture by shaking mechanically on an end-over-end shaker at 20 ± 1 °C for 24 h followed by centrifugation, and the residues of the herbicide in the extracts were determined by HPLC (Waters, Milford, MA, USA). Recoveries were greater than 95% of the herbicide applied to the soil. IZX residues from water samples were also determined by HPLC. The IZX dissipation data in soils and water were fitted to a first-order kinetics equation, $C = Co\ e^{-kt}$, where C is the IZX concentration at time t (days), Co is the initial herbicide concentration, and k (day^{-1}) is the degradation constant, and the half-lives ($t_{1/2}$) were calculated. Dissipation data were described using a first-order kinetic model to estimate half-lives ($t_1/_2$) for both the original and compost-amended soils. Soil dehydrogenase activity (DA) was measured according to the method described by García et al. [39], using INT (Merck, Darmstadt, Germany) as the substrate. Additional methodological information is provided in the Supplementary Materials (Text S2).

2.4. Leaching Experiments

To evaluate IZX leaching, triplicate disturbed PVC columns (30 cm × 5 cm i.d.) were filled with soils from both the original and compost-amended treatments and preconditioned with a 0.01 M $CaCl_2$ solution (Panreac, Castellar del Vallès, Spain), allowing 24 h for the excess solution to drain. To minimize losses of soil during the experiment, the top 5 cm of the columns was filled with sea sand (Panreac, Castellar del Vallès, Spain) and the bottom 5 cm with sea sand plus glass wool (Panreac, Castellar del Vallès, Spain). Subsequently, an IZX solution was applied to the top of each column to achieve a dose equivalent to 0.4 kg a.i./ha. After 24 h, the columns were irrigated daily with 50 mL of 0.01 M $CaCl_2$, and the leachates were analyzed using HPLC. At the end of the experiment, the soils were sectioned into four 5 cm segments to determine the remaining IZX, which was extracted following the procedure described for the dissipation experiments. Additional information on the leaching assays is provided in the Supplementary Materials (Text S3).

2.5. The Herbicide

Imazamox (IZX) was selected as a commonly applied herbicide for weed control in rice crops; its chemical name is 2-[(RS)-4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl]-5-methoxymethylnicotinic acid, with a molecular formula of $C_{15}H_{19}N_3O_4$ (Figure 2). The IZX analytical standard (purity > 95%) was obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany). The compound exhibits high water solubility at 20 °C (626 g L^{-1}), a vapor pressure of 6.3×10^{-8} mPa at 20 °C, and a relatively high melting point (166.3 °C). Under ambient conditions, it occurs as a solid white powder and has a molecular weight of 305.34 g mol^{-1} [40]. Details of the IZX analytical determination are provided in the Supplementary Materials.

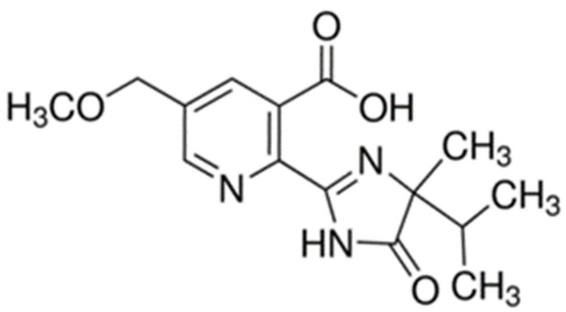

Figure 2. Chemical structure of the IZX herbicide.

IZX concentrations were quantified by high-performance liquid chromatography (HPLC) using a Waters 2695 E system equipped with a photodiode array detector (Waters 2996) and an autosampler (Waters, Milford, MA, USA). Chromatographic separation was achieved using a Kinetex column (150 × 4.6 mm, 5 μm particle size) maintained at 30 °C (Phenomenex, Torrance, CA, USA). The mobile phase consisted of acetonitrile (Fisher Scientific, London, UK) and water (20:80, v/v) containing 0.01 M phosphoric acid (Panreac, Castellar del Vallès, Spain), delivered at a flow rate of 1 mL min^{-1}. The injection volume was set at 25 μL, and UV detection was carried out at 255 nm. Under these conditions, the elution time for IZX was 3.5 min. Quantification was performed using external calibration curves constructed from standard IZX solutions at concentrations of 0.1, 0.5, 1, 2, 5, and 10 μM. Method repeatability was assessed through six consecutive injections of IZX standards. This evaluation was additionally performed on a different day and using different media (distilled water, 0.01 M $CaCl_2$, and an extracting agent) to assess reproducibility. The method showed satisfactory linearity and precision, with coefficients of determination (R^2) $\geq$ 0.999 and relative standard deviations below 2%. Analysis of control samples (without IZX) at the UV spectral maxima of IZX confirmed the absence of interfering peaks at the herbicide retention time. Under these experimental conditions, the limits of detection and quantification, calculated as the IZX concentrations resulting in signal-to-noise ratios of 3:1 and 10:1, respectively, were 0.011 μM and 0.037 μM, respectively. Finally, the IZX concentrations of different samples were quantified against linear calibration curves of chromatographic peak area versus IZX standards.

2.6. Statistical Analyses

The data were analyzed using ANOVA in the SPSS software (version 27.0). A two-way ANOVA model was applied to evaluate the interaction between management and year. Additionally, one-way ANOVA was conducted for each factor separately (management and year) to assess statistical differences among management treatments within each year and within the same management across different years. Two-way ANOVA was selected because it allowed us to evaluate the main effects of management and year simultaneously, as well as their potential interaction, which was relevant to determine whether the response variables were influenced independently or jointly by both factors. In addition, one-way ANOVA was applied when the objective was to assess the effect of each factor separately, either comparing management treatments within each year or comparing years under the same management treatment. This combination of analyses provided a clearer understanding of both individual and combined factor effects. Significant differences were determined at $p < 0.05$ using Duncan's test. Prior to ANOVA, all data were checked for homogeneity of variances and normality of residuals. Possible correlations among the different parameters were analyzed using Pearson's correlation coefficient at two levels of significance $p < 0.05$ and $p < 0.01$. Pearson's correlation coefficient was selected because the variables analyzed met the assumptions of linearity and approximate normal distribution, making this test appropriate for evaluating the strength and direction of linear associations among parameters. The significance thresholds of $p < 0.05$ and $p < 0.01$ were used because they represent conventional levels widely accepted in statistical analysis to indicate moderate and strong evidence against the null hypothesis, respectively. These two levels were applied consistently throughout the work to distinguish between correlations of different degrees of statistical support.

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3. Results and Discussion

3.1. Sorption–Desorption Studies

The sorption–desorption isotherms of Imazamox (IZX) under the different agricultural management systems are presented in Figure 3. In all cases, the experimental data showed a good fit to the Freundlich model, with determination coefficients (R^2) $\geq$ 0.909 in 2018 and $\geq$0.921 in 2019 (Table 1). Most n_f values were close to unity, indicating that IZX sorption was largely independent of the applied concentration (Figure 3; Table 1). The IZX sorption was significantly influenced by the management regime ($p < 0.001$) (Table 1).

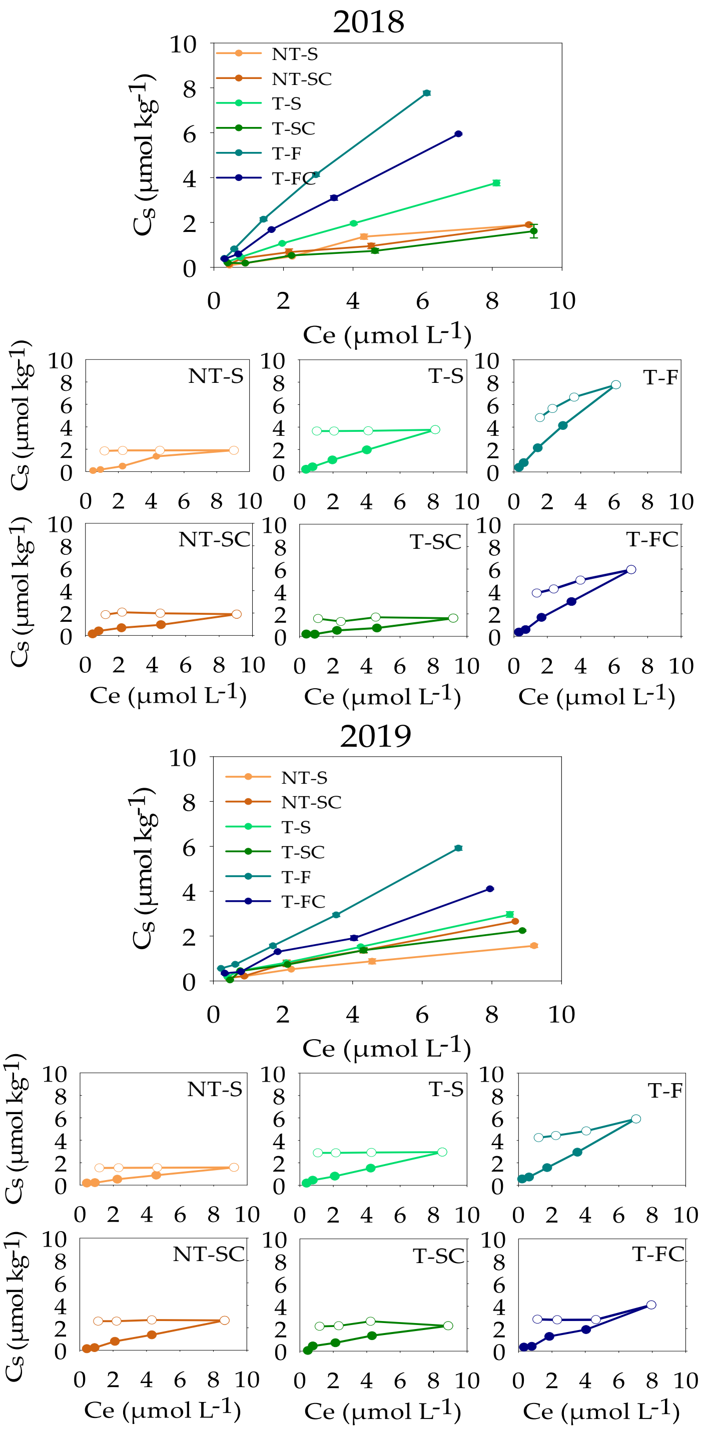

Figure 3. Influence of different management systems on Imazamox sorption–desorption parameter. Error bars denote one standard error of the mean. The filled symbols (●) represent sorption, whereas the open symbols (○) represent desorption.

Table 1. Imazamox adsorption–desorption parameters.

	n_f	K_d	$R^2_{sorption}$	% D †	$R^2_{desorption}$
2018					
NT-S	1.01 dB	0.222 aA	0.909	2.66 aA	0.955
NT-SC	0.841 bA	0.276 bA	0.927	2.59 aA	0.978
T-S	0.904 bA	0.520 cB	0.998	3.24 aB	0.923
T-SC	0.765 aA	0.215 aA	0.968	2.52 aA	0.953
T-F	0.992 cdA	1.37 eB	0.997	37.6 cB	0.999
T-FC	0.917 bcA	0.914 dB	0.980	35.1 bA	0.939
2019					
NT-S	0.856 abA	0.220 aA	0.943	2.87 aA	0.998
NT-SC	0.894 abA	0.307 bA	0.972	2.62 aA	0.976
T-S	0.853 abA	0.404 cA	0.979	2.47 aA	0.937
T-SC	0.779 aA	0.343 bB	0.921	2.01 aA	0.979
T-F	0.942 bcA	0.951 eA	0.935	28.3 bA	0.952
T-FC	0.810 abA	0.578 dA	0.934	31.9 bA	0.982
M	**	***		***	
Y	**	***		*	
M × Y	*	***		*	

The values reported for nf, Kd, and desorption (D) represent mean values. Treatments are as follows: no-tillage and sprinkler (NT-S), conventional tillage and sprinkler (T-S), conventional tillage and flooding (T-F), and the corresponding regimes with compost amendment (NT-SC, T-SC, and T-FC). ANOVA factors: M: Management; Y: Year; M × Y: Interaction Management × Year.; *, ** and *** significant at p levels of 0.05, 0.01 and 0.001, respectively. Different letters denote significant differences ($p < 0.05$): lower-case letters indicate differences between treatments within the same year, while upper-case letters indicate differences between years within the same treatment. R^2 is the coefficient of determination. † The percentage of D was calculated after three desorption cycles.

The Kd values were significantly influenced by the agricultural management system, with differences between years, as demonstrated by the significant management × year interaction ($p < 0.001$; Table 1). In the unamended soils, Kd values ranged from 0.222 to 1.37 in 2018 and from 0.220 to 0.951 in 2019 (Table 1). For both years, the IZX sorption was consistently lower in soils under collected from sprinkler irrigation, particularly under no-tillage conditions, where the Kd values were up to 6.2 and 2.6-fold lower in NT-S and T-S, respectively, compared with the flooded tillage system (T-F) (Table 1). This behavior can be attributed to the higher soil pH values observed under sprinkler irrigation compared with flooding conditions (Table S1). Similar results were reported by Fatino et al. [41], who studied four different agricultural soils and observed lower Kd values in those soils with higher pH (7.2–7.4) compared with soils of lower pH (6.2–6.7). Accordingly, a strong negative correlation between Kd and soil pH was found when only the original soils were considered ($r = -0.978$, $p < 0.01$). In agreement with Bresnahan et al. [42] and Saini et al. [43], these results indicate that the increase in soil pH associated with sprinkler irrigation promotes the deprotonation of IZX carboxyl groups, thereby reducing the proportion of cationic and neutral species available for sorption onto soil colloids. Consequently, the use of sprinkler irrigation instead of flooding in rice cultivation, regardless of the tillage management, causes an increase in pH, leading to a reduction in the adsorption capacity of IZX, thereby potentially increasing the potential risk of IZX transport and water contamination.

Compost application modified the IZX sorption behavior under conventional tillage and led to a significant reduction in the sorption capacity regardless of the irrigation system. Thus, in these treatments, the Kd values were 2.4- and 1.5-fold lower in 2018 and 1.2- and 1.6-fold lower in 2019 for T-SC and T-FC, respectively, relative to their non-amended counterparts (Table 1). These decreases in IZX sorption under conventional tillage management can be mainly attributed to the increase in soil pH induced by compost application. The soil pH increased from 6.27 to 6.89 and from 6.29 to 6.62 in the T-S and

T-SC treatments in 2018 and 2019, respectively, and from 5.52 to 5.92 and from 5.64 to 6.11 in the T-F and T-FC treatments over the same years (Table S1). Accordingly, the Kd values were strongly and negatively correlated with the soil pH ($r = -0.922$, $p < 0.01$). Thus, an increase in soil pH promotes a higher proportion of IZX (pKa 2.3 at 25 °C) in its anionic form within the soil solution. This negatively charged species shows reduced affinity for soil constituents and may be electrostatically repelled by negatively charged soil colloids and compost-derived organic matter, ultimately leading to decreased sorption. In contrast, under no-tillage conditions, the values of Kd increased significantly in amended soil compared to the unamended soil, in both years of the study (Table 1). This result can be attributed to the higher soil pH in NT-S (≥6.5 in both years of study, Table S1), such that the application of compost in this management system did not produce pronounced changes in the soil pH. Under these conditions, the increase in total organic carbon (TOC) content and the improvement in its quality (humic acids, HA) resulting from the application of compost may be responsible for the increase in the adsorption capacity of IZX in NTS-C management. Similar results were described by Undabeytia et al. [44], who indicated the increased sorption of imazaquin, an Imidazolinone herbicide like IZX, following organic amendment with olive mill waste, particularly in loamy sand soils.

The experimental desorption (D) data of IZX were satisfactorily described by the Freundlich equation, with determination coefficients (R^2) ≥ 0.923 in 2018 and ≥ 0.937 in 2019 (Table 1). The desorption was significantly affected by the applied soil management regime ($p < 0.001$). This effect varied between years, as demonstrated by the significant management × year interaction ($p < 0.05$; Table 1). In the unamended soils, a markedly higher reversibility of IZX was observed under soil collected from flooded conditions compared with soil collected from sprinkler irrigation in both years. Hence, the desorption values were 14.1- and 11.6-fold lower in 2018 and 9.9- and 11.5-fold lower in 2019 in the NT-S and T-S treatments, respectively, relative to the flooded tillage system (T-F) (Table 1). This pattern is likely related to the lower soil pH values recorded under flood irrigation. Accordingly, a strong negative and significative correlation was found between IZX desorption and soil pH ($r = -0.926$; $p < 0.05$), indicating that lower pH conditions enhance the desorption of IZX from the soil. Our results are consistent with those of Saini et al. [43], who indicated that, at low soil pH (≤5.9), the amount of IZX adsorbed was higher than at high pH (≥6.2), but the amount readily desorbed was also higher.

The use of compost led to decreases in D values, particularly under flooded irrigation in the first year of the study. Accordingly, in 2018, the IZX D values declined by 1.07-fold for T-FC compared with TF; in contrast, in the second year of the study, no significant changes were observed between them (Table 1). The reduction in desorption values may be related to the porous nature of organic matter in soil, which can trap IZX molecules and thereby reduce the desorption rate [44,45].

Therefore, our results indicate that IZX sorption and desorption is strongly influenced by the soil pH. These findings highlight that modifications in soil management and irrigation practices in rice cultivation can significantly alter the soil properties, leading to important changes in the adsorption and desorption of IZX processes that are crucial for determining the environmental fate of pesticides. However, the knowledge of IZX mechanisms sorption, which is quite important for accurately assessing its environmental fate, is still very limited [46] and will need to be examined in future studies.

3.2. Dissipation Studies

The dissipation curves of Imazamox (IZX) under the different agricultural management systems are presented in Figure 4, together with the dehydrogenase activity (DA) values recorded throughout the dissipation experiment. IZX half-lives ($t_1/_2$) were estimated by fitting the experimental dissipation data to a first-order kinetic model, finding high coefficients of determination ($R^2 \geq 0.872$ for 2018 and $R^2 \geq 0.851$ for 2019; Table 2), thereby confirming the suitability of the applied model.

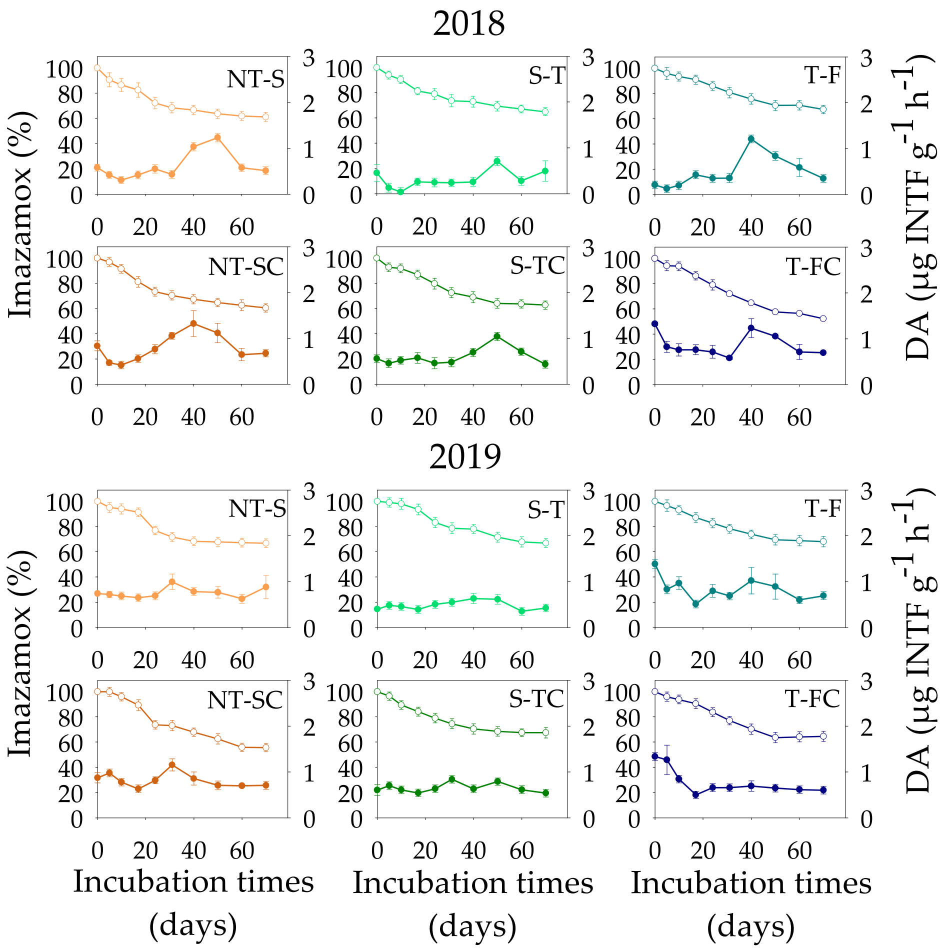

Figure 4. Influence of different management systems on Imazamox dissipation (○) and dehydrogenase activity (●). Error bars denote one standard error of the mean.

Table 2. Imazamox dissipation parameters and dehydrogenase activity.

	$t_{1/2}$ (Days)	R^2	DA (μg INTF g^{-1} h^{-1})
2018			
NT-S	87.9 bA	0.872	5.37 bcA
NT-SC	93.2 cB	0.903	7.17 cdA
T-S	108 dA	0.907	3.10 aA
T-SC	91.8 cA	0.938	5.88 bcA
T-F	125 eA	0.962	4.67 abA
T-FC	70.3 aA	0.979	7.70 dA
2019			
NT-S	107 cB	0.851	7.53 cB
NT-SC	73.5 aA	0.955	8.19 dA
T-S	115 dB	0.953	4.81 aB
T-SC	117 deB	0.898	6.51 bB
T-F	120 eA	0.858	7.69 cdB
T-FC	95.3 bB	0.938	7.82 cdA
M	***		***
Y	***		***
M × Y	***		**

Half-lives: $t_{1/2}$; DA: dehydrogenase activity considering all incubation times under soil condition. Treatments are as follows: no-tillage and sprinkler (NT-S), conventional tillage and sprinkler (T-S), conventional tillage and flooding (T-F), and the corresponding regimes with compost amendment (NT-SC, T-SC, and T-FC). ANOVA factors: M: Management; Y: Year; M × Y: Interaction Management × Year; ** and *** significant at p levels of 0.01 and 0.001, respectively. Different letters denote significant differences ($p < 0.05$): lower-case letters indicate differences between treatments within the same year, while upper-case letters indicate differences between years within the same treatment. R^2 is the coefficient of determination.

In unamended soils, the $t_1/_2$ values ranged from 87.9 to 125 days in 2018 and from 107 to 120 days in 2019. These values fall within the ranges reported by Buerge et al. [47], who described $t_1/_2$ between 2 and 120 days, and by Junkes et al. [48] for another herbicide belonging to the Imidazolinone family, with values between 42 and 182 days in Brazilian rice soils managed under continuous flooding and intermittent irrigation. Overall, these findings confirm the high persistence of herbicides from this family and their potential to accumulate in soils, posing risks to sensitive rotational crops and non-target organisms. The IZX $t_1/_2$ values were significantly influenced by the applied management practices ($p < 0.001$; Table 2). In addition, a significant management × year interaction was detected ($p < 0.001$), indicating that the management effects differed between the two study years. In this regard, in 2018, the $t_1/_2$ values of IZX decreased by factors of 1.42 and 1.16 in the NT-S and T-S treatments, respectively, compared with the T-F treatment, and 1.12 and 1.05 for 2019, respectively (Table 2). These results indicate that IZX dissipation proceeded more rapidly under aerobic than under anaerobic conditions, which may be associated with the higher soil pH values recorded in sprinkler-irrigated soils compared to flood-irrigated treatments. Indeed, when considering only unamended soils, a significant negative correlation was observed between $t_1/_2$ and soil pH ($r = -0.978$; $p < 0.01$). In soils with a lower pH, herbicide molecules tend to interact more strongly with soil particles, thereby slowing dissipation processes [49,50]. Furthermore, under sprinkler irrigation, conventional tillage (T-S) resulted in higher $t_1/_2$ values than no-tillage (NT-S), increasing them by factors of 1.23 in 2018 and 1.07 in 2019 (Table 2). This pattern may be explained by the higher microbial activity recorded under NT-S compared with T-S, as reflected by the dehydrogenase activity (DA) throughout the dissipation study (Table 2). This behavior is characteristic of Imidazolinone herbicides, which act as weak acids or bases depending on environmental pH [51], leading to enhanced sorption and increased persistence in soil [52]. In this context, the adoption of sprinkler irrigation in rice cultivation could be considered an alternative to traditional flooding due to the increase in pH, which mitigates IZX residue accumulation and its environmental risks.

Regardless of the management conditions, a clear effect of compost application on IZX dissipation was observed (Table 2), with the exceptions of the NT-SC treatment in 2018 and the T-SC treatment in 2019. The herbicide persistence decreased by factors of 1.18 and 1.78 in the T-SC and T-FC treatments, respectively, more than in their corresponding unamended soils (T-S and T-F), in 2018, and 1.46 and 1.26 in the NT-SC and T-FC treatments, respectively, more than in their corresponding unamended soils (NT-S and T-F), in 2019. Similar trends have been reported by Sánchez-Terrón et al. [28] and Gamíz et al. [27] using oak and holm oak biochar amendments, respectively, which resulted in reduced IZX persistence in soil. Comparable effects of compost amendment, under different crop managements, have also been described for other rice herbicides, such as Azimsulfuron and Bispyribac-sodium, showing decreased persistence following compost application [32,33]. This behavior may be attributed to the high total organic carbon (TOC) content and the degree of compost humification, particularly the humic acid (HA) fraction, which can stimulate microbial activity and enhance the biotic degradation of the herbicide. In fact, the values of dehydrogenase activity DA registered through the dissipation experiments were increased by factors of 1.34, 1.90, and 1.65 in the NT-SC, T-SC, and T-FC soils, respectively, compared to their corresponding unamended soils (NT-S, T-F and T-F) in 2018, and 1.09, 1.35, and 1.02 for 2019, respectively (Table 2). Thus, the IZX $t_{1/2}$ values were significantly and negatively correlated with the TOC ($r = -0.978$; $p < 0.01$), HA ($r = -0.703$; $p < 0.01$), water soluble organic carbon ($r = -0.457$; $p < 0.01$), and dehydrogenase activity (DA) ($r = -0.414$; $p < 0.01$). These results are consistent with those previously published by Su et al. [50], who observed that increased organic matter content in amended soils promoted changes in microbial activity and increased the dissipation rates of Imazapic, another Imidazolinone herbicide. Overall, these results highlight the relevance of

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organic amendments, such as compost, as an effective strategy to accelerate the dissipation of persistent herbicides such as IZX and to reduce their environmental impact, especially under flooding management, where IZX showed the highest persistence. However, the decrease in the persistence of IZX could be related to the reduced efficacy in weed control, which should be examined in future studies.

3.3. Leaching Experiments

Figure 5 showed the cumulative breakthrough curves of IZX under the different agricultural management systems. In addition, Table 3 summarizes the amounts of IZX recovered and leached from the soil columns at the conclusion of the leaching experiment. Across all treatments, the IZX breakthroughs remained below 1.03 pore volumes in 2018 and 0.695 pore volumes in 2019 (Figure 5), consistent with its high mobility and potential to contaminate water resources.

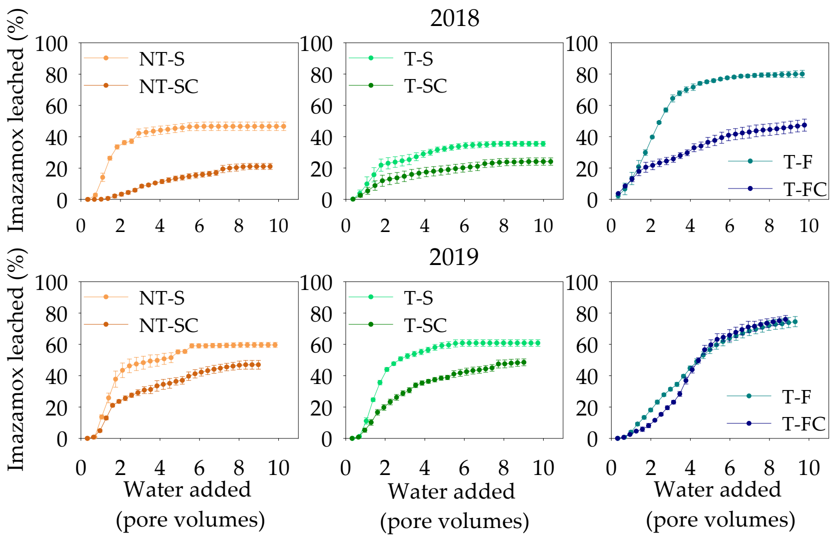

Figure 5. Influence of the different management regimes on cumulative leaching curves of Imazamox. Error bars denote one standard error of the mean.

Table 3. Imazamox leaching parameters.

	Initial Pore Volume †	Total Leached (%)	Total Extracted (%)	Not Recovered (%)
2018				
NT-S	0.715 bA	46.7 cA	4.08 cA	49.3 bB
NT-SC	1.03 cB	21.0 aA	3.02 bcA	75.9 cB
T-S	0.357 aA	35.5 bA	8.11 dB	56.4 bB
T-SC	0.370 aA	24.1 aA	1.59 abA	74.3 cB
T-F	0.345 aA	80.0 dA	0.00 aA	20.0 aA
T-FC	0.349 aA	47.4 cA	2.14 bcA	54.4 bB
2019				
NT-S	0.687 cA	59.6 abB	4.99 bcA	35.4 bcA
NT-SC	0.641 abA	47.0 aB	4.56 bB	48.5 dA
T-S	0.695 cB	60.8 bB	6.46 cA	32.7 bcA
T-SC	0.644 abB	48.5 aB	4.09 bB	47.4 dA
T-F	0.664 bcB	74.5 cA	0.00 aA	25.5 abA
T-FC	0.630 aB	75.9 cB	8.15 dB	15.9 aA
M	***	***	***	***
Y	***	***	**	***
M × Y	***	*	***	*

The data are presented as means. Treatments are as follows: no-tillage and sprinkler (NT-S), conventional tillage and sprinkler (T-S), conventional tillage and flooding (T-F), and the corresponding regimes with compost amendment (NT-SC, T-SC, and T-FC). ANOVA factors: M: Management; Y: Year; M × Y: Interaction Management × Year; *, ** and *** significant at p levels of 0.05, 0.01 and 0.001, respectively. Different letters denote significant differences ($p < 0.05$): lower-case letters indicate differences between treatments within the same year, while upper-case letters indicate differences between years within the same treatment. † Pore volume for initiation of the herbicide's leaching.

The leaching of IZX was significantly influenced by the management regime (p < 0.001). Moreover, a significant interaction between management regime and year was detected (p < 0.05), indicating that the effect of management differed between the two experimental years (Table 2). In unamended soils, up to 80% of the applied IZX leached in 2018 and 74.5% in 2019 (Table 3), slightly below the 90% reported by Khatem et al. [53] for a soil with a higher pH than ours (pH 8.20). Although the IZX sorption was significantly lower in NT-S and T-S compared to T-F, the highest total leaching occurred in the T-F treatment. Specifically, compared to the T-F treatment, the leaching from NT-S and T-S was reduced by factors of 1.71 and 2.25, respectively, in 2018, and by 1.25 and 1.23 in 2019 (Table 3). These results may be explained by the higher sorption reversibility and increased persistence under soil collected from flood irrigation conditions compared to soil collected from sprinkler irrigation, regardless of the tillage system applied. Indeed, when considering only unamended soils, the percentage of leached IZX correlated positively with D (r = 0.725; p < 0.01) and $t_{1/2}$ (r = 0.629; p < 0.01), highlighting the link between sorption–desorption, persistence, and leaching processes.

Our results revealed a clear trend in the impact of compost on IZX leaching, independent of the treatments. The addition of compost reduced IZX leaching in the NT-SC treatment from 46.7% to 21.0% and from 59.6% to 47%, in the T-SC treatment from 35.5% to 24.1% and from 60.8% to 48.5%, and in the T-FC treatment from 80% to 47.4% and from 74.5% to 75.9% for the years 2018 and 2019, respectively (Table 3, Figure 5). This effect could be associated with the reduction in IZX $t_{1/2}$ detected in all amended treatments compared to the corresponding unamended treatments (Table 2). Similar results were reported by López-Piñeiro et al. [33], who observed that, in rice soils, compost application reduced losses of the herbicide Bispyribac-sodium through leaching. In fact, the total leaching of IZX was positively correlated with the $t_{1/2}$ values (r = 0.443; p < 0.01), showing that higher IZX dissipation rates may decrease herbicide availability and, consequently, its potential for leaching. Therefore, applying compost derived from olive mill waste as an organic amendment to rice soils not only represents a sustainable alternative for its disposal, but may also serve as an effective strategy to reduce the risk of water contamination by IZX. Consistent with these results, Terrón-Sánchez [28] reported a positive and significant correlation between IZX persistence and the amount of leached IZX; however, in their study, the rice soils were amended with biochar. In addition, the decrease in IZX losses by leaching in amended soils could be related to the level of organic matter humification. Indeed, there was a significant and negative correlation between the percentage of leached IZX with AH (r = −0.390; p < 0.05), indicating that the leaching capacity of IZX depends on the organic matter transformed into humic substances.

At the end of the leaching experiment, IZX retention was determined to be significantly influenced by the management regime (p < 0.01) (Table 3), with the exception of the T-F treatment, in which no IZX was recovered (Table 3). The absence of detectable IZX in the T-F soil columns could be associated with the higher amount of IZX leaching for this treatment. Furthermore, the trend observed in the total extracted IZX, although not always statistically significant, indicates that the T-S treatment, characterized by the lowest leaching, allowed the highest recovery of IZX (>6.47%, Table 3). This is supported by a significant negative correlation between the percentages of total extracted and total leached IZX (r = −0.512; p < 0.05) among the unamended treatments. In reference to unamended management under soil collected from sprinkler irrigation, regardless of the tillage system, the application of compost (NT-SC and T-SC) reduced the amount of IZX extracted from the leaching columns (Table 3). These findings may be attributed to irreversible adsorption (Table 1) and/or increased IZX dissipation (Table 2) following compost application, as evidenced by the higher amounts of unrecovered IZX in compost-amended soils, regardless of the tillage and irrigation management implemented (Table 3). In fact, the extracted IZX was negatively correlated with the $t_{1/2}$ values (r = −0.345; $p < 0.05$) and positively correlated with the desorption values (r = 0.609; $p < 0.01$).

4. Conclusions

The present study demonstrates that the environmental fate of IZX is closely controlled by soil properties, which are modified by the implementation of different agricultural rice management practices. In flood-irrigated soils, the persistence of IZX and the risk of losses through leaching remained; in contrast, in soils irrigated via sprinkler—particularly when combined with compost application—the leaching capacity was limited regardless of the tillage system. The reduction in leaching was mainly associated with lower herbicide persistence and a higher degree of irreversible adsorption, reflecting a functional improvement in soil health linked to increased organic carbon content, enhanced organic matter quality, and higher microbial activity. Therefore, sprinkler irrigation in combination with olive mill waste compost application caused changes in soil properties that could contribute to mitigating the risks associated with IZX in rice crop management. Nevertheless, future research is needed to validate the results under field conditions, including effectiveness studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16060609/s1, Texts S1–S3; Table S1: Selected soil parameters (0–20 cm layer); Figure S1. Mean rainfall, mean maximum and minimum temperatures registered at the field location during 2018 and 2019; Figure S2. Schematic representation of the laboratory experiments conducted with field-collected soils from each treatment.

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Abbreviations

The following abbreviations are used in this manuscript:

IZX	Imazamox
NT-S	No-tillage and sprinkler irrigation
NT-SC	No-tillage and sprinkler irrigation with compost amendment
T-S	Conventional tillage and sprinkler irrigation
T-SC	Conventional tillage and sprinkler irrigation with compost amendment
T-F	Conventional tillage and flooding irrigation
T-FC	Conventional tillage and flooding irrigation with compost amendment
$t_1/_2$	Half-lives
DA	Dehydrogenase activity

D	Desorption
TOC	Total organic carbon
HA	Humic acid

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