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Determination of residue levels of imazamox herbicide (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1 H-imidazol-2-yl]-5-(methoxymethl)-3-pyridinecarboxylic acid) in soil and drainage water

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ABSTRACT

The study was completed in Kırklareli province in the Thrace region of Turkey in 2014. The study was conducted to determine the primary material and derivatives of imazamox (imazapic, imazapyr, imazethapyr, and imazaquin), the most commonly used herbicide in sunflower production in the region, which leaves residues in soil and drainage water. The study was completed using two soils, three imazamox doses, and three irrigation applications in three repetitions. According to the results obtained from the study, we determined 9.3–146.1 $\mu g\ L^{-1}$ imazamox residue in T1 soil (sandy loam, pH: 4.05, CEC: 4.77 me 100 g^{-1}) while 11.7–221.6 $\mu g\ L^{-1}$ imazamox residue was found in T2 soil (loam, pH: 7.28, CEC: 19.36 me 100 g^{-1}). The imazamox identified in the upper layers of soil was proportionally higher compared with the lower levels. The assessment of residue amounts overtime indicated an order of first week > sixth week > harvest. Imazamox and its derivatives (imazapyr, imazapic, imazethapyr, and imazaquin) were encountered in water samples taken from drains, and the values varied from 0.10 to 17.3 $\mu g\ L^{-1}$. The residues of imazamox and derivatives identified in a limited number of drainage water samples were above the permitted 0.1 $\mu g\ L^{-1}$ value for pesticides by the TS-266 standard and 96/83/EC and 75/440/CEE.

Keywords: Imazamox; Soil; Drainage water; Residue; Sunflower

1. Introduction

Due to the rapidly increasing world population and increasing food requirement, many inputs are used in agricultural production to obtain high yields while maintaining the quality. Moreover, attempts are made to receive optimum benefit from these inputs. Application of pesticides is a significant agricultural input since pesticides protect plants from the effects of disease and harmful weeds, thus, increasing product amounts and quality [1]. The ratio of pesticide usage, which is also called chemical weeding, is over 95% in pest control. Crop quality and yield decrease by approximately 60% ratio if pesticide use is avoided. Therefore, the usage of plant conservation products is indispensable to control pests, which cause yield loss [2]. In addition to the advantages of pesticides, an unavoidable input of modern agriculture, there are many disadvantages in terms of human health and environmental pollution. Pesticides or the transformation products may remain in the nourishment, soil, water, and air as a result of their intensive and callous usages. The study of residual risk and negative effects of pesticide usage in agricultural products should be emphasized [1]. Although the use of pesticides in Turkey is lower compared with developed countries [3], the intensive agriculture and problematic chemical contents of pesticides in terms of the environment and health have increased the importance of knowledgeable and controlled use of pesticides [4,5].

Thus, determining the residues left by pesticides used in soil, water and on products carries great importance.

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Sunflower is an important oil plant, globally. In Turkey, the sunflower production from the Thrace region comprises 56.3% of the country's production and imazamox comes first with the ratio of 72% within the herbicides.

IMI technology was developed as a weed control choice allowing the use of imidazolinone herbicides in sunflower agriculture. Traditional sunflowers are susceptible to imidazolinone herbicides, whereas IMI sunflower hybrids have been modified to survive with resistance to this herbicide [6].

In this study, the residual amounts of imazamox herbicide and its derivatives in soil, their removal from soil, and mixing with drainage water were studied.

2. Material and methods

2.1. Study area

The research was completed in the Atatürk Soil Water and Agricultural Meteorological Research Institute, located 4 km west of Kırklareli in the northern part of the Marmara region. Kırklareli province is located at 41°42′ north latitude and 27°12′ longitude at 190 m elevation. During the development period for sunflowers (May-June-July-August) in 2014 a total of 217.9 mm of rainfall was recorded. The mean temperature for May-June-July-August was measured as 21.9°C.

2.2. Soil properties

The study was completed using 195 L pots with 70 cm diameter (base 60 cm diameter) and 60 cm height. The surface area of the pots was 0.39 m^2. A total of 54 pots were used, with the base of the pots filled with 5 cm thick, 12–19 mm crushed stone, with the properties of soil above the stones given in Table 1.

2.3. Herbicide with imazamox as active material

Herbicide containing imazamox was used in the trials. The herbicide used had a water-soluble formulation and contained 40 g L^{-1} imazamox active material. The herbicide was used against the weeds broomrape, jungle rice, cocklebur, tumbleweed, nightshade, red-root foxtail, white goosefoot, and knotgrass with 125 mL da^{-1} in the 4–10 true leaf period of the sunflower plant. Imzamox (2-[4,5-dihydro-4-methyl-4-(1-methyl ethyl)-5-oxo-1 H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) has 305.33 molecular weight and is a compound used as a herbicide. It has a stable structure with a half-life at pH 5, 7, and 9 and is a stable compound against destruction by hydrolysis [7,8].

2.4. Traits of sunflowers used in the trials

IMI tolerant Sanay MR sunflower seeds. Sanay MR is robust, reliable, and high-yield IMI sunflower variety with high rates of resistance to IMI-group pesticides. Sunflower planting was completed at the beginning of May.

2.5. Trial method

The trial was carried out according to randomized parcels split parcels trial design with three repetitions in 54 pots as two different soil, three different imazamox doses, and three different irrigation water applications (Table 2).

Sunflower plant was cultivated earlier in April after the pots were filled with soil. Imazamox herbicide was applied in a pulverized form at the seedling stage (4–10 leaves). The plants were irrigated thrice, according to the growth phases of the plant.

2.6. Irrigation and irrigation times

To determine the irrigation times, three stages based on the head formation, flowering time, and sap formation periods when the plant was sensitive to the water were identified [9]. Head formation corresponded to 70–75 d after planting; the beginning of flowering began nearly 15 d after head formation and sap formation period began nearly 15 d after flowering. To determine the water deficiency in pot soils with the gravimetric methods [10], field capacity, 25% less than field capacity and 25% more than field capacity were used. On a variable basis, the amounts of water applied to each pot are shown in Table 3.

Table 2
Trial variables

Soil type	Imazamox dose (mL da^{-1})	Subvariables (water levels)		
		S1 (75%)	S2 (100%)	S3 (125%)
T1	I1 = 0	$T_1I_1S_1$	$T_1I_1S_2$	$T_1I_1S_3$
	I2 = 5	$T_1I_2S_1$	$T_1I_2S_2$	$T_1I_2S_3$
	I3 = 7.5	$T_1I_3S_1$	$T_1I_3S_2$	$T_1I_3S_3$
T2	I1 = 0	$T_2I_1S_1$	$T_2I_1S_2$	$T_2I_1S_3$
	I2 = 5	$T_2I_2S_1$	$T_2I_2S_2$	$T_2I_2S_3$
	I3 = 7	$T_2I_3S_1$	$T_2I_3S_2$	$T_2I_3S_3$

Table 1
Some physical and chemical properties of soils in the trial area

Trial area	pH	Volume weight (g cm^{-3})	Texture class					Organic matter (%)	CEC me 100 g^{-1}
			% Clay	% Silt	%Sand				
T1	4.95	1.82	8.33	12.50	79.17	Loamy sand	0–30 cm	0.41	4.77
							30–60 cm	0.39	
T2	7.28	1.50	22.92	31.25	45.83	Loam	0–30 cm	1.99	19.36
							30–60 cm	1.76	

Table 3
Applied and drained water amounts

Trial variables			Applied water (L)				Drained water amount (total for three irrigations) (L)
			1st irrigation	2nd irrigation	3rd irrigation	Total	
T1	I1	S1	26	29	25	80	–
		S2	35	38	34	107	9.8
		S3	44	48	42	134	11.8
	I2	S1	26	29	25	80	–
		S2	35	38	34	107	8.4
		S3	44	48	42	134	12.6
	I3	S1	26	29	25	80	–
		S2	35	38	34	107	10.1
		S3	44	48	42	134	14.4
T2	I1	S1	30	31	26	87	–
		S2	40	41	35	116	7.6
		S3	50	51	44	145	12.4
	I2	S1	30	31	26	87	–
		S2	40	41	35	116	5.1
		S3	50	51	44	145	9.9
	I3	S1	30	31	26	87	–
		S2	40	41	35	116	6.7
		S3	50	51	44	145	10.7

2.7. Sampling and sample preparation

2.7.1. Water sampling

After the three-period irrigations of sunflower plant, the drainage waters were collected, and the amounts were determined (Table 3). Then, samples (30 mL each) were taken from the water samples for analysis.

2.7.2. Soil sampling

Soil samples were taken as soon as imazamox was administered, at the end of the first week after imazamox administration, at the end of the sixth week, and at harvest sampling from 0 to 30 cm and 30 to 60 cm soil depths.

2.7.3. Preparation of soil samples for analysis

Soil samples (1 g) with 10 mL added acetone were mixed in a vortex mixer. Then, 1 mL tetrabutylammonium hydroxide and 2 mL iodomethane were added to these samples, and this was continuously mixed for 1.5 h in a 45°C water bath. After 1.5 h, the mixture was left to cool. Using an evaporation system under nitrogen, all of the organic phases in the mixture was evaporated. Then, 2 mL ultrapure water, 15 mL diethylether:*n*-hexane (1:2) mixture was added and this was vortexed for 2 min. Water was removed from the extract using 12 g anhydrous sodium sulfate. The supernatant (filtrate) was evaporated using nitrogen until dry. The residue was dissolved by adding 1 mL hexane. The hexane phase was taken into an injector. It was filtered through a 0.45 μm diameter (PTFE) injection filter and placed in a vial and injected into the GC-MS device for analysis [11].

2.7.4. Preparation of water samples for analysis

Water samples (30 mL) were extracted with 30 mL dichlormethane (30 min mixing and waiting). After the shaking procedure in a separating funnel, the dichlormethane phase was separated. The dichlormethane phase was placed in a falcon centrifuge tube and evaporated until dry in an evaporation system under nitrogen, and then dissolved in 2 mL acetone. Then, 200 μL tetrabutyleammonium hydroxide (cas no: 2052-49-5 Sigma Aldrich) and 400 μL iodomethane (cas no: 74-88-4, Sigma Aldrich) were added and continuously mixed in a shaking water bath for 1.5 h at 40°C. After 1.5 h, the supernatant was evaporated using an evaporation system under nitrogen until dry. Subsequently, 2 mL ultrapure water and 15 mL diethylether:*n*-hexane (1:2) mixture were added and vortexed for 2 min. Using 12 g anhydrous sodium sulfate, the water was removed from the extract and the remaining supernatant (organic filtrate) was evaporated under nitrogen until dry. The residue was dissolved by adding 1 mL hexane. The hexane phase was taken into an injector. It was filtered through a 0.45 μm diameter (PTFE) injection filter and placed in a vial. A GC and GC-MS device were used to determine residue in drainage water samples [11,12]. The GC-MS SIM chromatograms for soil and water samples are shown in Figs. 1 and 2.

2.7.5. Analysis methods and optimization studies

In optimization studies, the concentrations in mg L^{-1} had LOD value from 1.7E-7 to 1.3E-4, LOQ values from 1.0E-4 to 5.7E-7; for concentration studies in μg L^{-1} had LOD values of 0.040917 to 1.9915E-05 and LOQ values of 0.13639 to 6.64E-05.

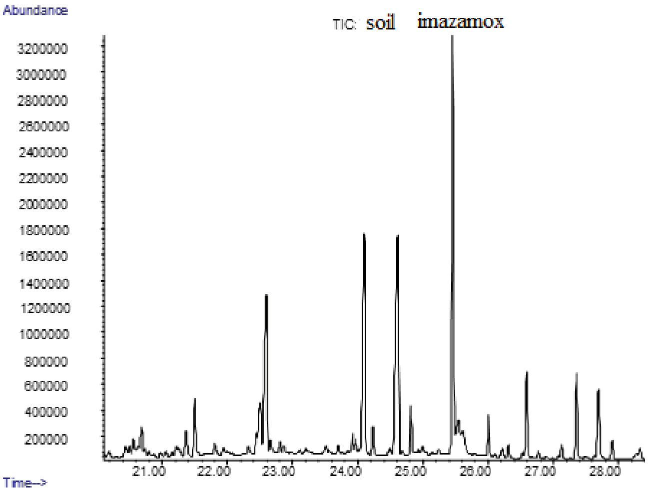


Fig. 1. GC-MS SIM chromatogram for soil samples.

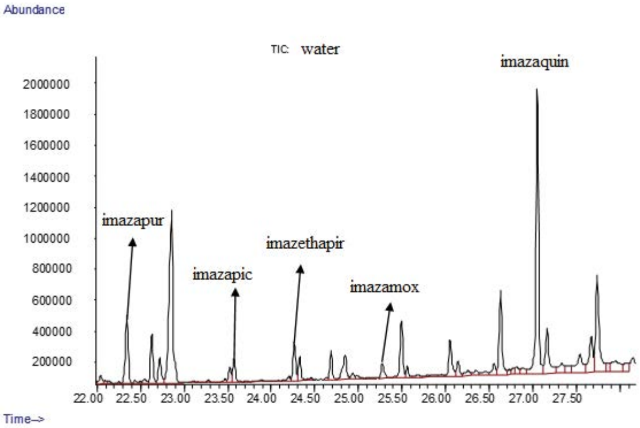


Fig. 2. GC-MS SIM chromatogram for water samples.

2.7.6. Recovery studies

Before beginning analyses, recovery studies were performed. Soil and water samples had standards with concentrations of 25, 50, 100, and 200 µg L^{-1} added to determine recovery rates (Table 4).

2.8. Analysis and assessment

The imazamox residues determined in soil had variation analysis completed according to the basis stated in Ref. [13] for assessment. Statistical assessments were completed with the JMP (ANOVA) program. Analyses were performed at the 0.01 and 0.05 significance levels and the LSD test was applied to the significant variables.

3. Results and discussion

Analyses of soils used to fill the pots did not show any traces of imazamox or its derivatives. As there was no residue of imazamox and derivatives in soils before the trial, the area where soil was taken from to fill the pots should not have used the herbicide previously. Thus, the residue was not encountered in I1 (no imazamox application) variable application.

The results of analyses of soil samples encountered only imazamox as the main material. In soil, the imazamox derivatives of imazapic, imazapyr, imazethapyr, and imazaquin were not encountered. Previous studies have shown that imazamox could stay for long periods as it may be mobile in soil environments. There are many factors affecting the presence of imazamox in the soil. In a variety of soil types, the imazamox half-life varies from 35 to 118 d. The mean half-life of imazamox in soils was determined as 65 d [14].

In the Thrace region, imisazolinone group herbicides were used in sunflower production [15] in Edirne. Moreover, the product rotation price studies showed that canola plants planted 4 months after sunflower plants had a reduced product yield of 23.7%, with the plant output reduced by 35.7%. Sugar beet planted 9 months after application had 11.6% reduction in yield and 26.7% reduction in plant output rates. This result showed that imazamox herbicide might remain in soil 9 months later.

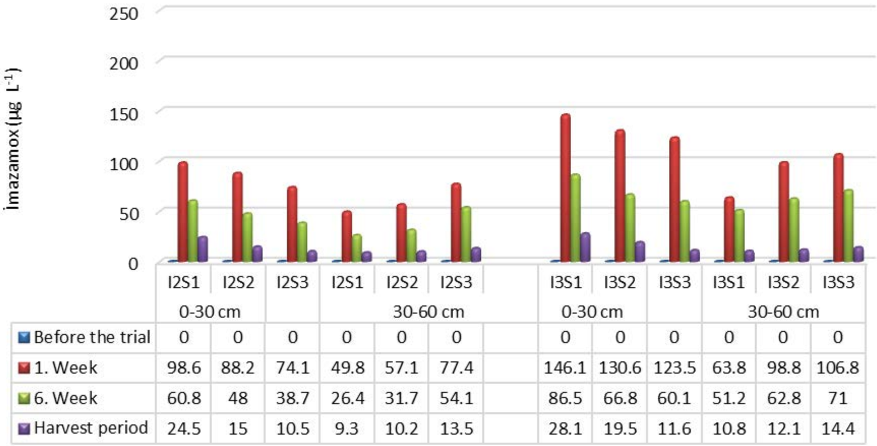
In our study, the statistical analysis results for the identified imazamox residue amounts and values are shown in Figs. 3–4 and Table 5.

T1 variable (sandy loam, pH: 4.95, and CEC: 4.77 mg 100 g^{-1}) had the highest imazamox residue amount of 146.1 µg L^{-1} for the I3S1 variable (7.5 mL da^{-1} imazamox and 70% water irrigation) 0–30 cm layer in samples from the first week after imazamox application. The lowest residue amount was 9.3 da^{-1} µg L^{-1} for a T1I2S1 variable in the 30–60 cm soil layer in samples from the harvest period (Fig. 3). Similar results were obtained from the T2 soils (loam, pH: 7.28, and CEC: 19.36 me 100 g^{-1}). The highest residue amount was 221.6 µg L^{-1} for T2I3S1 0–30 cm soil layer in samples from the first week, with lowest residue amount of 11.7 µg L^{-1} for T2I1S2 (Fig. 4).

Statistical analysis results for residue amounts are shown in Table 5. Soil type, imazamox doses, and irrigation were 99% effective on the imazamox residue amounts determined. Examination of the variable interactions (Table 5), such as soil type and depth, soil type and depth and irrigation, soil type and depth and imazamox dose, soil type and depth

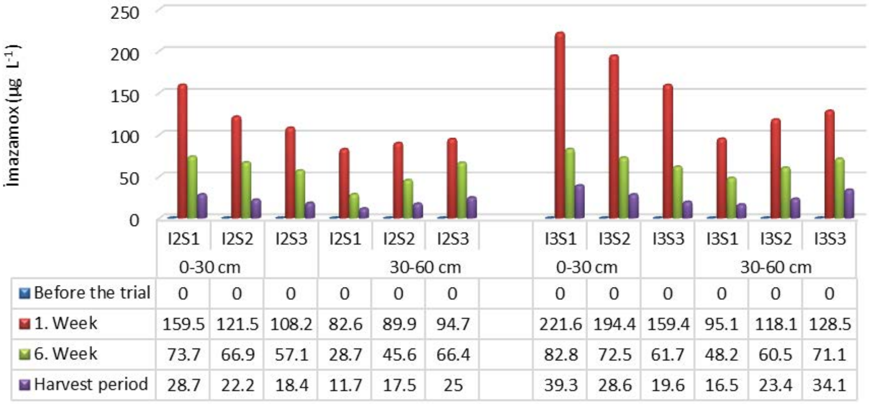
Table 4
Recovery rates (%, $n = 15$)

	Imazapyr	Imazapic	Imazethapyr	Imazamox	Imazaquin
Water	76–102	84–99	95–96	87–98	91–104
STD deviation	±9.35	±3.03	±0.52	±4.58	±3.89
Soil	78–91	84–96	80–93	92–99	99–104
STD deviation	±5.30	±3.74	±4.34	±2.32	±2.07



	I2S1	I2S2	I2S3	I2S1	I2S2	I2S3	I3S1	I3S2	I3S3	I3S1	I3S2	I3S3
	0-30 cm			30-60 cm			0-30 cm			30-60 cm		
🟦 Before the trial	0	0	0	0	0	0	0	0	0	0	0	0
🟥 1. Week	98.6	88.2	74.1	49.8	57.1	77.4	146.1	130.6	123.5	63.8	98.8	106.8
🟩 6. Week	60.8	48	38.7	26.4	31.7	54.1	86.5	66.8	60.1	51.2	62.8	71
🟪 Harvest period	24.5	15	10.5	9.3	10.2	13.5	28.1	19.5	11.6	10.8	12.1	14.4

Fig. 3. Imazamox residue amounts determined in T1 soils (μg L^{-1}).



	I2S1	I2S2	I2S3	I2S1	I2S2	I2S3	I3S1	I3S2	I3S3	I3S1	I3S2	I3S3
	0-30 cm			30-60 cm			0-30 cm			30-60 cm		
🟦 Before the trial	0	0	0	0	0	0	0	0	0	0	0	0
🟥 1. Week	159.5	121.5	108.2	82.6	89.9	94.7	221.6	194.4	159.4	95.1	118.1	128.5
🟩 6. Week	73.7	66.9	57.1	28.7	45.6	66.4	82.8	72.5	61.7	48.2	60.5	71.1
🟪 Harvest period	28.7	22.2	18.4	11.7	17.5	25	39.3	28.6	19.6	16.5	23.4	34.1

Fig. 4. Imazamox residue amounts determined in T2 soils (μg L^{-1}).

and irrigation, and the imazamox dose, was effective on imazamox residues.

The residue amounts determined in the first week after imazamox application in both soil types was higher compared with the residue amounts determined in the sixth week. The residue amounts determined in the sixth week were higher compared with the residue amounts at harvest. Thus, the order of residue amounts was first week > sixth week > harvest. After pesticides are applied to soil or plants, they pass through processes such as evaporation, leaching from the soil profile, accumulation, and contamination. Each pesticide has a half-life simultaneously.

The effect of all these factors indicates that pesticides experience degradation overtime according to chemical structures and are linked to environmental conditions, and thus, are lost. Previous studies show that pH, clay percentage in the soil, organic matter amounts, cation exchange capacity, and soil humidity affect pesticide degradation. With the increase in pH value of the soil, the imazamox half-life duration increases [16–18], so more imazamox residues may be found in soils. With the increase in clay amount in soil, the adsorption rate of imazamox increases [17,19–23] and the imazamox residue amounts identified in soils with low clay amounts are also low. Organic matter also affects the degradation of imazamox in soil and its adsorption by soil colloids. The organic matter amount in T2 soils was 4.8 times the organic matter amount in T1 soils. Thus, the residue amounts were higher in the soil with higher organic matter amount [19,21–23]. Although the difference in organic matter amounts in the two soils was greater, the difference in residues was not as high. The presence of organic matter, on the one hand, increases the adsorption of imazamox in soil, while it increases the microbial activity in soils [24,25]. The increasing microbial activity increases herbicide degradation. Degradation is slower as microbial activity is lower in acid soils. In both soil types, the residue amounts in the upper levels were higher than in lower levels [16]. In the trial, irrigation application used three different humidity levels. Residue analysis at different humidity levels (Figs. 3 and 4) indicated more residue encountered in the trial with deficient irrigation. In fact, increasing humidity amounts shortens the half-life of imazamox [15,25–28].

In this study, irrigation was applied during head formation, sap formation, and at the beginning of flowering when sunflower plants are sensitive to water. Deficient humidity in soil was determined with the gravimetric method, and three

Table 5
Variance analysis results and LSD classification of determined imazamox residue amounts

Sources of variance		Variance analysis *P* values		
		1st week	6th week	Harvest
ST and De		<0.0010**	<0.0001**	<0.0019**
IR		0.0142*	0.4945	0.4919
ST and De and IR		<0.0001**	<0.0001**	<0.0001**
ID		<0.0001**	<0.0001**	<0.0001**
ST and De and ID		<0.0001**	<0.0001**	<0.0001**
IR and ID		0.1411	0.4706	0.2337
ST and De and IR and ID		0.0001**	0.0016**	0.0001**
Re (ST-De) and Ra		0.0890	0.8074	0.3263
Re*IR (ST-De) and Ra		0.5888	0.4166	0.4978
Comparison of means		Imazamox (μg kg^{-1})		
ST and De	T2 (0–30 cm)	107.19 a	46.08 a	17.40 a
	T1 (0–30 cm)	73.43 b	40.10 b	14.33 b
	T2 (30–60 cm)	67.65 b	38.14 b	12.11 b
	T1 (30–60 cm)	50.41 c	33.03 c	7.82 c
	LSD (0.05)	6.03	4.87	2.34
Variable (ID)	I3	132.20 a	66.26 a	21.48 a
	I2	91.81 b	51.75 b	17.27 b
	I1	1.421e–14 c	0.00 c	5.329e–15 c
	LSD (0.05)	6.00	4.25	1.27
IR	S1			14.07 a
	S2			12.37 b
	S3			12.31 b
	LSD (0.05)			1.26
	P (%)			5

*5% significance level ($P < 0.05$), **1% significance level ($P < 0.01$).
a, b, c: used for grouping in the LSD (least significant difference) test for comparison of means, a, b, and c represent each group.
ST: soil type, De: depth, IR: irrigation, ID: imazamox dose, Ra: random, Re: repeat.

different application forms were applied. In the S1 variable application, 25% deficient water was applied, S2 variable applications had deficient humidity completed, and S3 applications had 25% excess water application, and the water was allowed to drain. Imazamox accumulation in soils with deficient amounts of irrigation and imazamox leaching into drainage water, and thus, mixed with underground water were investigated in this study. As planned, there was no water drainage in S1 applications. In S2 applications, a small amount of water passed into drainage due to the water load on the surface of soils. The water drained after irrigation had identification studies completed for imazamox and derivatives.

Residue determination studies using water analyses with GC-MS found values determined for imazamox and the derivatives were below the LOD values.

Based on the adsorption time determined with GC-MS, a second study was performed with GC. GC can conduct analyses at the pictogram (pg) level. The results shown in Table 6 are the values obtained by GC. Moreover, recovery studies and the results determined by GC support the GC-MS studies.

Analyses of drainage water were used to determine the imazamox residues, and residues of the imazamox derivatives of imazapyr, imazapic, and imazethapyr. However, there was no homogeneity between the variable applications and repetitions. Statistical analyses were not performed due to the lack of homogeneity. Although some parallels regarding residues were expected from the same variable applications, some were not determined. In fact, in some conditions, herbicides may be washed from soils and mix with drainage water, while under other conditions, water may pass through cracks in soil and intervals where the soil is in contact with the pot to directly mix with drainage water. The extreme value of 111.67 μg L^{-1} determined in drainage water may be due to the reasons mentioned earlier.

When this extreme number is excluded from the assessment, the other residue amounts in drainage water were determined from 0.10 to 17.3 μg L^{-1}. In T1 soils, with high sand proportion, and low pH, organic matter, and CEC values, there was more residue determined in drainage water. Application of organic matter from an olive oil factory to soil increased soil adsorption of simazine and imazaquin

Table 6
Imazamox, imazapyr, imazapic, and imazethapyr determined in drainage water, μg L^{-1}

Variable			Repeat	Imazapyr			Imazapic			Imazethapyr			Imazamox		
				02.07.2014	11.07.2014	22.07.2014	02.07.2014	11.07.2014	22.07.2014	02.07.2014	11.07.2014	22.07.2014	02.07.2014	11.07.2014	22.07.2014
T1	S2	I2	1	–	2.10	–	–	1.60	–	–	1.40	–	–	3.45	–
			2	–	4.60	–	–	5.14	–	–	3.36	–	–	1.70	–
			3	–	0.67	–	–	10.20	–	–	2.23	–	–	–	–
		I3	1	–	11.00	2.29	–	–	1.91	–	3.70	2.29	–	1.43	4.87
			2	–	1.01	–	–	–	–	–	0.11	–	–	–	–
			3	–	0.60	17.30	–	–	–	–	0.87	–	–	–	111.7
	S3	I2	1	–	–	–	–	–	–	–	–	–	–	–	–
			2	–	–	–	–	–	–	–	–	–	–	3.30	–
			3	–	–	–	–	–	–	–	–	–	–	–	–
		I3	1	13.80	–	–	11.70	–	–	3.10	–	–	2.63	–	–
			2	2.90	–	–	13.50	–	–	7.68	–	–	–	–	–
			3	–	–	–	–	–	–	–	–	–	–	–	–
T2	S2	I2	1	3.05	–	–	–	–	–	–	–	–	–	–	–
			2	8.40	–	–	–	–	–	–	–	–	–	–	–
			3	–	–	–	–	–	–	–	–	–	–	–	–
		I3	1	–	–	–	–	–	–	3.68	–	–	–	–	–
			2	–	–	–	–	–	–	3.81	–	–	–	–	–
			3	–	–	–	–	–	–	–	–	–	–	–	–
	S3	I2	1	6.54	–	–	–	–	–	–	–	–	–	–	–
			2	4.76	–	–	1.08	–	–	–	–	–	–	–	–
			3	–	–	–	–	–	–	–	–	–	–	–	–
		I3	1	8.50	–	3.80	–	–	4.20	–	3.17	0.95	1.47	0.12	–
			2	2.90	3.56	6.80	–	–	6.26	–	3.37	5.62	0.10	0.10	–
			3	–	1.14	3.60	–	–	2.27	–	–	0.42	–	3.56	–

and reduced leaching of these herbicides and mixing with underground water [29]. The same study showed that chemicals such as imazamox, cymoxanil, chorpyridos, cyprodinil, fenitrothion, fludioxonil, flufenoxuron, and iprovalicarb enter water and this water passes through soil and soil+organic matter mixtures. The half-life of all pesticides is shorter in soil with added organic matter compared to soil without organic matter. The leaching effects on imazamox and derivatives in imazamox dose applications and irrigation rates were observed more clearly in T2 soils. The residue amounts were determined to be higher with the increase in imazamox doses applied and 25% excess water application increased leaching of pesticides and derivatives.

A study of rice fields showed that water rapidly disintegrated imazamox in rice paddies [30]. The research emphasized that in spite of the short half-life of imazamox, the herbicide may be carried by water from rice paddies into clean water resources. In conventional agriculture, water sampling on the second day after imazamox herbicide application determined 9.5 μg L^{-1} residue, while 8 d later the residue amount was 3.7 μg L^{-1} and sampling 50 d later found that the residue amounts had fallen to 0.2 μg L^{-1}. Water sampling of underground water on different days after imazamox application did not encounter imazamox residues.

The residue amounts of imazamox and derivatives identified in a limited number of drainage water samples, the values were above the 0.1 μg L^{-1} value permitted for pesticides according to human consumption water regulations (TS-266 standard (0.10 μg L^{-1}) [31], 98/83/EC [32] and 75/440/CEE [33] decision on human health by the European Union).

The assessment of the residue amounts in drainage water, according to human consumption water regulations, identified numbers that were significantly higher than the permissible limits. However, drinking water wells are found at very deep levels (around 200 m) and are covered with layered clay formations. The clay fraction prevents contamination by pesticide residues. Soil colloids strongly adsorb pesticide molecules before reaching these layers.

4. Conclusion

4.1. Soil Environment

- The study performed sampling at three different time intervals and the residue amounts determined were in the order first week > sixth week > harvest.
- The determined residue amount increased with increase in the dose of imazamox.
- The persistence of imazamox in soil increased with the increase in pH value.
- The 0–30 cm soil layer had higher residue amounts compared with the 30–60 cm soil layer.
- The increase in organic matter and clay amounts increased the residue amounts in soil.
- With the increase in soil humidity amounts, the imazamox residue amounts were reduced.

4.2. Aqueous environment

- Homogeneity was not found for drainage water samples on a repeat basis.
- Imazamox and its derivatives (imazapyr, imazapic, imazethapyr, and imazaquin) were found in some water samples.
- Imazamox residue amounts in water samples varied from 0.10 to 17.3 μg L^{-1} and residues were determined more in T1 soils.
- The residue amounts of imazamox and derivatives identified in a limited number of drainage water samples were above the 0.1 μg L^{-1} value permitted for pesticides by TS-266 standard and 98/83/EC and 75/440/CEE.

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