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Determination of Xenobiotics Present in Soil using LC-HRMS and QuEChERS Method

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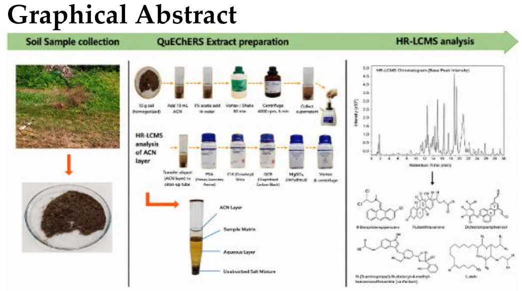
Abstract

Human activities have resulted in the presence of xenobiotic substances like pharmaceuticals, pesticides, and cosmeceuticals in the environment. Its presence presents hazards to the environment; therefore, it is important to keep a check on its concentrations in environmental samples like soil and water. Detection of these xenobiotics is very important for taking preventive measures to ensure the safety of ecosystems and living things from any adverse effects of these contaminants. In this study, pollution due to xenobiotic substances was assessed in the fertile agricultural land located near the Tons ecotone region in Prayagraj, India, which has been extensively used for agricultural purposes. Quick, Easy, Cheap, Effective, Rugged, and Safe (QuEChERS) extraction method along with liquid Chromatography–High-Resolution Mass Spectrometry (LC-HRMS) was used to detect and analyze xenobiotic substances present in soil samples. The extraction method was specifically designed for the extraction of soil samples, and the chromatographic analysis exhibited good performance and characteristics. LC-HRMS analysis of the QuEChERS extract resulted in the identification of 27 xenobiotic substances, such as cyclohexylamine, enilconazole, o-desmethyllevomepromazine, tamoxifen, fludrocortisone acetate, and other xenobiotic substances.

Keywords: Soil: Xenobiotics: QuEChERS: LC-HRMS: Pharmaceuticals.

Graphical Abstract



Introduction

Xenobiotics, which include pharmaceuticals, pesticides, and cosmeceuticals, have become a subject matter of interest for researchers recently because of their deleterious impact on ecosystems and the environment (Mendoza et al., 2014). Although the efficiency and side effects of xenobiotics on their target species are considered prior to their widespread usage, the environmental hazards caused by them usually receive less attention. In light of the increasing use of xenobiotics, the possibility of their environmental contamination has risen considerably. Xenobiotics specifically can reach the environment through different means, including excretion by humans or animals, incorrect disposal by the producer or consumer of xenobiotics, and unsustainable farming practices. It has also been found that when xenobiotics are used for medicinal purposes, not all of the active components of xenobiotics are broken down by the body. The leftover amount reaches the environment either in its initial form or after metabolism (Carvalho et al., 2018; Boxall, 2004).

As a result, these substances are increasingly being identified as pseudo-persistent contaminants**,** meaning that even at low concentrations, their consistent presence poses a long-term threat to the environment and ecosystems. Several studies have reported the presence of minute quantities of a diverse range of xenobiotic compounds, including antibiotics, analgesics, hormones, steroids, and antiparasitics, in environmental samples such as water, soils, etc. (Baz-Lomba et al., 2016). The amassment of such compounds is largely driven by anthropogenic activities, such as human and animal excretion, industrial activity, combustion of fossil fuels, excessive use of agrochemicals, and the discharge of untreated chemical wastes in intensive agricultural practices (Alkorta and Garbisu, 2001).

The combination of QuEChERS and Liquid Chromatography-High-Resolution Mass Spectrometry (LC-HRMS) brings many benefits like high recovery for a broad range of polarity and volatility of xenobiotics, high processing volume with low amounts of organic solvents needed. However, few studies that concern the use of QuEChERS method for the extraction of diverse xenobiotics from soil samples have been published (Asensio-Ramos et al., 2010), and most of these xenobiotics have not been studied yet, although these xenobiotics are commonly present in soil. Combining the latest techniques of sample preparation with the LC-HRMS brings some advantages, such as high efficiency in processing, low cost of operation and high sensitivity. In recent years, LC-HRMS was used for the detection of residues and organic contaminants, such as residues of pesticides, pharmaceuticals and PCPs in environmental samples (Picó and Barceló, 2008; Leandro et al., 2007). QuEChERS technique is an effective method for the analysis of these contaminants in soil because of high performance and high speed of separation by chromatography.

This study seeks to evaluate the concentrations of xenobiotics such as pharmaceutical drugs, cosmeceuticals, and pesticides in fertile land around the ecotone of Tons River in Prayagraj, India. This study can help gain an insight into the pollution of agricultural lands as a result of unsustainable practices (Khan et al., 2023; Khan et al., 2025; Sharma et al., 2025), and thus, suitable remedial steps can be undertaken. In this study, the QuEChERS method with LC-HRMS has been used. To the best of our knowledge, the use of the QuEChERS method with the LC-HRMS for the extraction of xenobiotics from the soil samples in terms of molecular mass, adduct ion mass, and retention time has not been explored extensively in any other study. Potential xenobiotics have also been identified through the use of LC-HRMS.

Materials and Method

Sample Collection and Preparation

The collection of soil samples was done from fertile land near Tons river ecotone region, Prayagraj, India (Figure 1). Soil from the upper 10 cm was collected in polyethylene bag and subsequently transported to the laboratory for sieving (mesh size 1 mm) and the samples were oven-dried at a temperature of 30 °C for 24 h, then frozen and kept at −20 °C for subsequent analysis soil samples. Subsequently, the soil samples were subjected to QuEChERS extraction and LC-HRMS analysis.

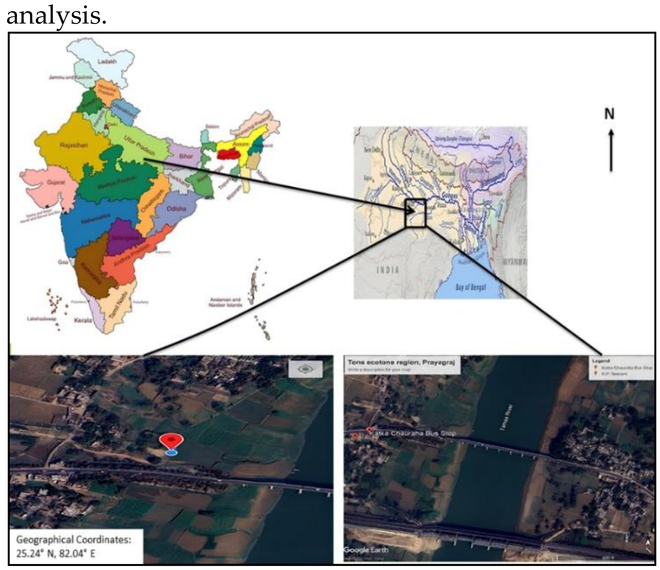


Fig. 1 Location of the study area of Tons River ecotone in Prayagraj, Uttar Pradesh, India (https://www.mapchart.net/india.html)

Reagents and Chemicals

HPLC-grade acetonitrile (ACN) from Sisco Research Laboratories Pvt. Ltd., and acetic acid and formic acid from Fisher Scientific Inc., USA, were used for sample preparation and mobile-phase preparation. Analytical reagent-grade anhydrous magnesium sulfate, Formic acid, acetic acid, sodium citrate dibasic sesquihydrate, sodium citrate tribasic dehydrate, and sodium chloride were from Sisco Research Laboratories Pvt. Ltd. and were used in the present research work. Magnesium sulfate was calcined at 450° C in a muffle furnace to remove moisture and residual phthalates to maintain its purity.

QuEChERS Approach for Xenobiotic Extraction

Solvent selection plays an important role in preparation of the sample, particularly in relation to the nature of the xenobiotics present. Widely used extraction solvents include ethyl acetate, acetone, and ACN. Among these, ACN offers distinct advantages, such as minimal interference from proteins, lipids, and other co-extracted matrix components, which contribute to its high recovery efficiency. Due to these benefits, ACN was selected as the extraction solvent in the QuEChERS experimental procedure. The QuEChERS experimental procedure provides high effectiveness and reliability in the extraction and determination of a diverse range of analytes like pesticides, fungal toxins, drug residues, illicit compounds, and other xenobiotics, both in solid and liquid matrices like environmental, food, pharmaceutical, biological, forensic matrices, etc. (Santana-Mayor et al., 2023). In this approach, a combination of magnesium sulfate ($MgSO_4$) and sodium chloride (NaCl) was added to enhance phase separation. This facilitated the formation of a well-defined upper organic layer, which yielded a substantial volume and was effectively utilised to achieve high analyte recoveries.

In the process of extraction of xenobiotics from the soil by QuEChERS method, 5 g of the soil sample was weighed in a 50 mL polypropylene centrifuge tube. To which, 2.5 mL of distilled water was added to hydrate it by soaking for 30 min. Next, 5 mL of 1% acetic acid in acetonitrile solution (0.5% v/v, formic acid) was added, and the tubes were agitated in a vortex mixer (Remi C-852) for 1 minute, and kept for 10 min. Further, anhydrous magnesium sulfate (4.0g), sodium chloride (4.0g), sodium citrate dibasic sesquihydrate (0.5g), and sodium citrate tribasic dihydrate (1.0g) were added, and the tubes were agitated in a vortex mixer (Remi C-852) for 1 min. Then, after 2 minutes, it was centrifuged at 5000 rpm for 5 minutes (Remi R-12C) (Prestes et al., 2012; García-Valverde et al., 2021) (Figure 2). After that, the supernatant was collected (Figure 3) and filtered using a Millex-GN nylon filter (0.20 μm, Millipore, Carrigtwohill, Ireland) prior to LC-HRMS analysis (Mahdavi et al., 2

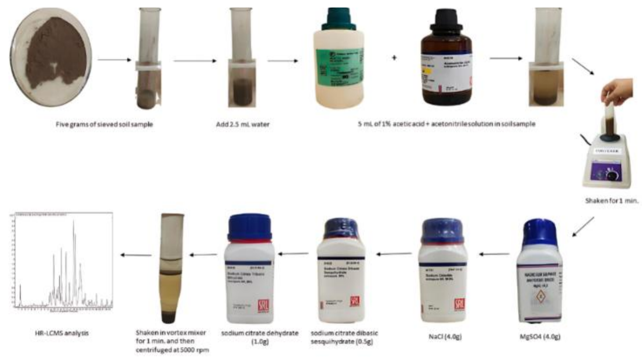


Fig. 2 Steps involved in QuEChERS approach for xenobiotic extraction from soil sample

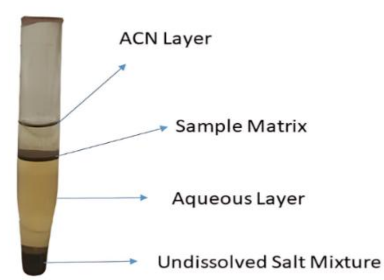


Fig. 3 QuEChERS extract having xenobiotics in ACN layer

LC-HRMS Analysis of QuEChERS Extract

QuEChERS extract of the formulation, that is, supernatant layer of ACN (which was collected after centrifugation during the extraction process of xenobiotics from soil by the QuEChERS technique) containing xenobiotics present in soil, was used for LC-HRMS analysis. For LC-HRMS analysis of the sample, high resolution liquid chromatography-quadrupole time-of-flight mass spectrometry (HRLCMS-QTOF-MS; Agilent Technologies, USA), with an electrospray ionization (ESI) source (Sophisticated Analytical Instrumentation Facility (SAIF), Indian Institute of Technology (IIT), Bombay) was used. Data acquisition was done through Agilent Mass Hunter Data Acquisition Software and Agilent Mass Hunter Qualitative Analysis B.06 as the data processing software. Identification and detection of xenobiotics were done using the dual AJS ESI ion mode of a Chip Cube, 6550 iFunnel Q-TOF 6550 (Agilent Technologies, USA) mass spectrometer with Electrospray Ionization (ESI) & Atmospheric Pressure Chemical Ionization (APCI) sources.

The stationary phase utilized is as follows: HypersilGOLD C-18 (2.1 × 100 mm, particle size: 3 μm), that is, octadecyl-bonded silica; 5 μL injection volume was injected through a needle, with an injection speed of 100 μL/min and a 5.0 sample flush-out factor. The combination of mobile phases comprised "solvent A" 100% water (H2O) (0.1% formic acid in water) and solvent B 100% acetonitrile (CH3CN) (90% acetonitrile, 0.1% formic acid, and 10% water) with a flow rate of 300 μL/min. The details of the mobile phase gradient are listed in Table 1. The acquisition method was selected as MS with a mass-to-charge (m/z) range of 120-1200 and a scanning rate of 1 spectrum/s. The settings for the iFunnel MS Q-TOF component of the instrument are controlled as follows: gas flow rate 13 L/min (250 °C), sheath gas flow rate 11 L/min (300 °C), and nebulizer gas pressure 35 psi. The capillary voltage was 3500 V and the nozzle voltage was 1000 V (Table 2). The both nebulizing and collision gases were nitrogen.

Table 1 Liquid chromatography gradient elution analysis program

Time/min	Flow rate (mL.min^{-1})	A%	B%	Pressure
1.00 min	0.300 mL/min	95.00 %	5.00 %	1200.00 bar
25.00 min	0.300 mL/min	0.00 %	100.00 %	1200.00 bar
30.00 min	0.300 mL/min	0.00 %	100.00 %	1200.00 bar
31.00 min	0.300 mL/min	95.00 %	5.00 %	1200.00 bar
35.00 min	0.300 mL/min	95.00 %	5.00 %	1200.00 bar

Table 2 HR-LC–MS/MS instrumental acquisition parameters

Instrument Parameter	**Setting / Value**
Ionization source	Dual AJS Electrospray Ionization (ESI)
MS absolute threshold	200 counts
MS/MS absolute threshold	5 counts
MS scan range (m/z)	120–1200
MS scan rate	1.0 spectra s^{-1}
MS/MS scan rate	1.0 spectra s^{-1}
MS/MS isolation width	Medium (~4 amu)
Maximum precursor ions per cycle	10
Precursor selection threshold	10,000 counts
Target ion count per spectrum	25,000 counts
Drying gas temperature	250 °C
Drying gas flow rate	13 L min^{-1}
Nebulizer pressure	35 psig
Sheath gas temperature	300 °C
Sheath gas flow rate	11 L min^{-1}
Capillary voltage (VCap)	3500 V
Nozzle voltage	1000 V
Fragmentor voltage	175 V
Skimmer 1 voltage	65 V
Octopole RF peak	750 V
Draw speed	100.0 μL min^{-1}
Eject speed	100.0 μL min^{-1}
Delay after sample draw	2.0 s
Sample flush-out factor	5.0
Injection volume	5.0 μL
Needle wash time	3.0 s
Mobile phase flow rate	0.300 mL min^{-1}
Low-pressure limit	0.0 bar
High-pressure limit	1200.0 bar
Maximum flow ramp-up	100.0 mL min^{-2}
Maximum flow ramp-down	100.0 mL min^{-2}
Total run time	30.0 min

Results and Discussion

The intensification of modern agricultural practices and increased exposure of agricultural land to different xenobiotics, along with limited knowledge regarding their proper disposal or management, have led to the release of their residues into environmental matrices such as soil and water bodies (Figure 4).Thus, from previous studies, it was found that QuEChERS sample preparation method is suitable for analysis of xenobiotic residues in different vegetables, fruits, soil, sewage sludge samples, etc. The soil pollutants extracted through the QuEChERS method were subjected to LC-HRMS to trace out xenobiotics based on their retention time, experimental *m/z*, MS/MS fragments, database differences (library), xenobiotic class, and proposed compounds. MS data were obtained in the positive and negative ionization modes. Most of the *m/z* values for the formulation's xenobiotic compounds were between 122 and 772.

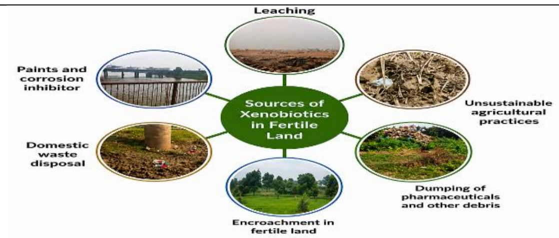


Fig. 4 Sources of Xenobiotics in fertile land.

Primary Screening of Xenobiotics Content in Soil Extract of Fertile Land

During the multiple reaction monitoring of the sample prepared for qualitative analysis, various xenobiotics were detected. Based on chromatographic retention time and fragmentation patterns obtained through high-resolution MS/MS, 27 xenobiotic compounds were detected in the fertile land of the ecotone while analysing the sample. The sample was run in positive and negative modes in LC-MS/MS, and then, as per the molecular mass of the compounds, the adduct ion mass was recorded from the output of MS (Sinha et al., 2019). For Cyclohexylamine, with a molecular mass of 99.1045, the compatibility mode yielded an adduct ion mass of 122.0936 and a retention time of 1.627 min in positive mode. While in Carboxymethyloxy succinate adduct ion mass of 790.4343 was identified in negative mode, corresponding to its molecular mass of 192.0291, with a retention time of 1.602 min. Similarly, Enilconazole or imazalil (IMZ), a fungicide (systematic), has a molecular mass of 296.0454 with an adduct ion mass of 319.0348 and a retention time of 8.641 min. in positive mode. The molecular mass, adduct ion mass, retention time, and other related parameters of the various xenobiotics reported in the LC-HRMS analysis of the QuEChERS extract of the soil sample are listed in Table 3.

Table 3 HR-LCMS analysis revealed pharmaceuticals and other xenobiotics identified in the soil extract of the QuEChERS analysis

Compounds	**RT (Minutes)**	**Mass (Daltons)**	**m/z**	**Polarity**	**Formula**	**Characteristics and toxicity**
Cyclohexylamine	1.627	99.1045	122.0936	Positive	$C_6 H_{13} N$	Corrosion inhibitor (Groenewold et al.,1996)
3-methyl-dodecanedioic acid	13.681	244.1707	243.1635	Negative	$C_{13} H_{24} O_4$	Nylon 6, 12, adhesives, powder coatings and paints, Corrosion inhibitor, complexing agent for lithium complex grease (Bertuzzi et al., 2000)
Carboxymethyloxysuccinate	1.602	192.0291	191.0218	Negative	$C_6 H_8 O_7$	Builders in detergent (Newsome and How, 1979)
Enilconazole or imazalil (IMZ)	8.641	296.0454	319.0348	Positive	$C_{14} H_{14} C_{12} N_2 O$	Fungicide (Ghosoph et al., 2007)
O-Desmethyllevomepromazine	10.249	314.1452	315.1525	Positive	$C_{18} H_{22} N_2 O S$	Antipsychotic, anxiolytic, sedative and analgesic (Kłys et al., 2003)
Tamoxifen	14.773	371.2265	372.2342	Positive	$C_{26} H_{29} N O$	Breast cancer treatment (Day et al.,

						2020)
CAY10510 or Prostaglandin F2α (PGF2α)	14.119	420.2326	443.221	Positive	C_{24} H_{33} F O_5	Treatment of glaucoma and eyelash hypotrichosis(Rahman et al., 2022)
Fludrocortisone acetate	15.923	422.2124	445.2019	Positive	C_{23} H_{31} F O_6	Anti-inflammatory and antiexudative properties (Hong et al., 2022)
13-Hydroxypergolide glucuronide	17.829	506.2095	507.2166	Positive	C_{25} H_{34} N_2 O_7 S	Xenobiotic metabolites (Stachulski and Meng, 2013)
4-[[5-(acetylamino)-1-methyl-1H-indol-3-yl]methyl]-3-methoxy-N-[(2-methylphenyl)sulfonyl]-Benzamide	18.12	505.1586	528.1503	Positive	C_{27} H_{27} N_3 O_5 S	Sulphonamide drug in veterinary medicine, antibacterial, used in combination with the anti-malarial drug pyrimethamine (Ovung and Bhattacharyya, 2021)
15-oxo-18Z-tetracosenoic acid	18.447	380.3253	403.3153	Positive	C_{24} H_{44} O_3	Treatments for demyelinating diseases, acquired immunodeficiency syndrome, cardiovascular diseases and chronic kidney disease, Alzheimer's disease (AD). (Li et al., 2019)
2,2'-Bipyridylamine	18.554	171.0788	194.068	Positive	C_{10} H_9 N_3	Tumour-preventive activity (Schödel et al., 1996)
Toxoflavine	18.871	193.0606	194.0678	Positive	C_7 H_7 N_5 O_2	Cytotoxicity and cell death specifically in breast cancer cells. (Wu et al., 2024)
Mebhydrolin	19.247	276.165	277.173	Positive	C_{19} H_{20} N_2	Antihistamines (Prokopenko et al., 2021)
Lipoxin	20.904	512.258	535.247	Positive	C_{25} H_{40} N_2 O_7 S	Anti-inflammatory (Batiha et al., 2022)

Trandolaprilat	21.652	402.2154	403.2227	Positive	$C_{22} H_{30} N_2 O_5$	Treatment of hypertension (Alfaro, Navarro-Retamal, and Caballero, 2020)
3'-N-Acetyl-4'-O-(14-methylpentadecanoyl)fusarochromanone	20.326	572.3798	595.368	Positive	$C_{33} H_{52} N_2 O_6$	Antimalarial (Watanabe et al., 2023; Mahdavian et al., 2014)
Desmethylhalofantrine	25.081	443.1029	442.0957	Negative	$C_{22} H_{22} Cl_2 F_3 N O$	Antimalarial (Bryson and Goa, 1992)
Haloperidol	24.901	375.144	374.1369	Negative	$C_{21} H_{23} Cl F N O_2$	Treatment of Delirium (Smit et al., 2023)
O-Desmethylquinidine	24.807	310.1641	355.1626	Negative	$C_{19} H_{22} N_2 O_2$	Antiarrhythmic potency (Ueda and Nickols, 1980)
N-(adamantan-1-yl)-1-(5-fluoropentyl)-1H-indole-3-carboxamide (STS-135) or 5F-APICA	23.876	382.244	381.2372	Negative	$C_{24} H_{31} F N_2 O$	Synthetic cannabinoids (SC), psychoactive substances. (Ameen, Brown, and Dennany, 2022)
13,14-dihydro-15(R,S)-hydroxy-16,16-difluoro Prostaglandin E1-d4	21.297	396.2598	441.2581	Negative	$C_{20} H_{30} D_4 F_2 O_5$	Erectile failure (Porst, 1996)
Lopinavir	20.916	628.3661	673.365	Negative	$C_{37} H_{48} N_4 O_5$	Antiretroviral drugs (Oldfield and Plosker, 2006)
Benoxinate	20.49	308.2066	353.2051	Negative	$C_{17} H_{28} N_2 O_3$	Anesthetic drug (Kasuya, Igarashi, and Fukui, 1987)
Lamprolobine	19.669	264.1807	309.179	Negative	$C_{15} H_{24} N_2 O_2$	Compound Kushen injection (CKI) for Cancers, Breast Cancer (Ye et al., 2022)
Cl-Amidine	19.205	310.1179	369.1319	Negative	$C_{14} H_{19} Cl N_4 O_2$	Suppresses colitis, IBD Inflammatory bowel diseases (IBDs), Crohn's disease and ulcerative colitis, chronic inflammatory conditions

						(Chumanevich et al., 2011)
N-omega-propyl-L-Arginine	19.036	216.1583	275.1725	Negative	$C_9 H_{20} N_4 O_2$	Treatment of schizophrenia (Klamer, Engel, and Svensson, 2004)

Relative Screening of Xenobiotics Content in Soil Extract of Fertile Land

The abundance of the xenobiotic compounds present in the samples is shown by their mass-to-charge ratio (m/z) peak intensities and by their corresponding chromatographic peak heights (Figure 5). The adduct ion mass (m/z) peaks were captured in MS/MS at their precise retention times to confirm these results (Singh et al., 2022). A total of 27 xenobiotic compounds of different classes were reported from the study site. Most of them are pharmaceutical wastes followed by synthetic reagents, which are frequently used as daily use products and pesticides.

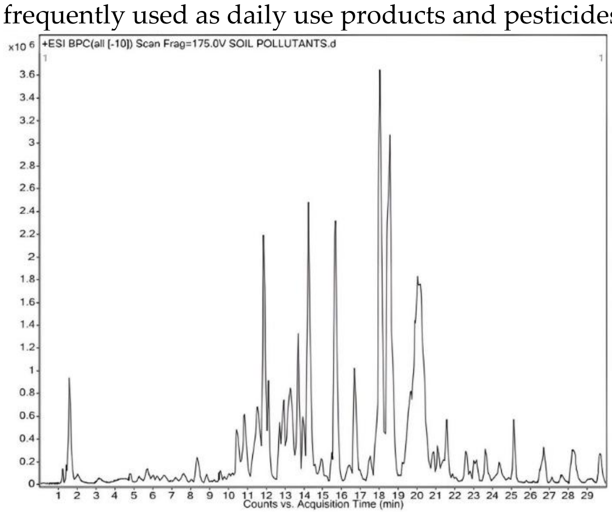


Fig. 5 HR-LCMS chromatogram of identified xenobiotics in the QuEChERS-extracted soil sample

The release of xenobiotics into soil has become more widespread due to modern farming practices, improper disposal of household waste near farmland, and the expansion of human settlements into agricultural areas. Furthermore, chemicals can leach from packaging materials into the environment, contaminating soil, water, and air. As soil is a very complex and variable matrix with considerable organic matter content, resulting in a decrease in the extraction efficiency, it often warrants the use of a clean-up procedure. Thus, in this study, the QuEChERS method was adopted for soil xenobiotic analysis, as it effectively simplifies sample preparation and ensures high recovery with minimal matrix interference (Kaczyński et. al.,2016). The xenobiotics extracted using the QuEChERS method were further analysed by LC-HRMS. A variety of techniques have been used globally in order to determine the concentration of pollutants in the environment. Among such techniques, LC-HRMS is considered one of the most reliable techniques for both qualitative and quantitative analysis. Due to its reliability, precision, and speed, LC-HRMS has emerged as the technique of choice in recent environmental and toxicology studies. Different studies have validated its reliability in determining the profile of pollutants in food, soil, and biological samples (Asensio-Ramos et al., 2010).

In this study conducted in a Tons ecotone region, 27 xenobiotics were detected in soil samples, comprising 23 pharmaceutical compounds, 3 domestic care products, and 1 pesticide residue. A comprehensive understanding of the presence of these xenobiotics in soil is essential for the estimation of their potential ecological impact and for developing sustainable management practices.

Potential Toxicity of Xenobiotics Found in Soil Sample

Xenobiotic substances found in soils (Figure 6) include those substances which have been identified earlier to be transported into flora and fauna via bioaccumulation, thereby causing biomagnification in the food chain, leading to serious dangers for organisms within the food chain. Cyclohexylamine has been detected in the soil collected from productive agricultural lands. It is an organic base of high strength, generally used as a corrosion inhibitor, and its toxicity has been found to be high when found in higher amounts (Groenewold et al., 1996). Laboratory experiments conducted on the same revealed that low concentrations of 0.01 M of Cyclohexylamine are toxic to aquatic plants like Lemna minor (duckweed) (Fromm, 1958).

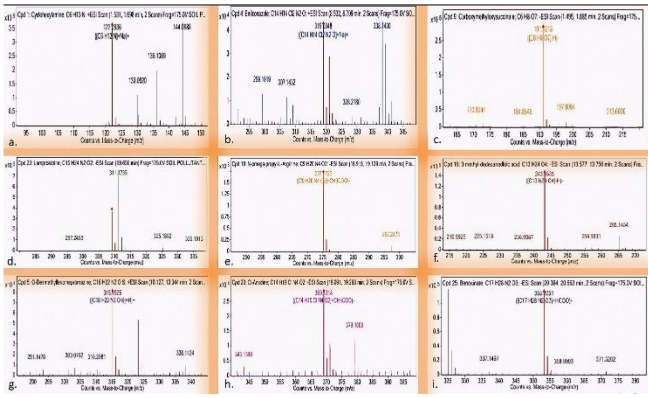


Fig. 6 Mass Spectra of some of the main pollutants present in QuEChERS extract of soil xenobiotics sample (identified by HR-LCMS). (a) Cyclohexylamine, (b) Enilconazole, (c) Carboxymethyloxysuccinate, (d) Lamprolobine, (e) N-omega-propyl-L-Arginine, (f) 3-methyl-dodecanedioic acid, (g) O-Desmethyllevomepromazine, (h) Cl-Amidine and (i) Benoxinate

Enilconazole, also known as Imazalil, reported in the soil sample, is a broad-spectrum systemic fungicide (Ghosoph et al., 2007). Despite its extensive use, research on the environmental impact of Enilconazole remains limited (Hof, 2001). Tamoxifen is a drug that disrupts endocrine function and is mainly prescribed for breast cancer treatment (Day et al., 2020). Though it has a therapeutic role in human medicine, its unintended exposure to the environment raises concerns towards its potential accumulation at various trophic levels in an ecosystem. Empirical evidence indicates that exposure to tamoxifen in plants results in a decline in chlorophyll and carotenoid content by disrupting their vital physiological functions. This suggests that tamoxifen, along with other such related pharmaceuticals, may adversely affect plant yield and development, emphasising further investigation into their impact on the environment and negative ecological consequences (Carvalho et al., 2014).
Fludrocortisone acetate (FCA), also known as 9-α-Fluoro-11β, 17α, and 21-trihydroxy-4-pregnene-3,20-dione acetate, is a synthetic steroid with anti-inflammatory and anti-exudative properties (Hong et al., 2022). A study showed that anti-inflammatory drugs have negative effects on morphological and physiological functions in plants. Exposure to anti-inflammatory drugs resulted in a decline in PI(abs), i.e. Performance Index of overall photosynthetic efficiency and Tfm (time to reach peak chlorophyll fluorescence) in the plant (Kalaji and Rastogi, 2017). These findings show the damaging effects of pharmaceutical pollutants on plant systems, particularly by the disruption of physiological functions like photosynthetic efficiency and growth. 4-[[5-(acetylamino)-1-methyl-1H-indol-3-yl]methyl]-3-methoxy-N-[(2-methylphenyl) sulfonyl] - Benzamideis a sulphonamide drug which is used in veterinary medicine as an antibacterial compound to treat livestock diseases such as gastrointestinal and respiratory tract infections and also as an anti-malarial drug to treat toxoplasmosis in warm-blooded animals (Ovung and Bhattacharyya, 2021). Such sulfonamides with a highly hydrophilic nature get accumulated in the roots of the plant (Tanoue et al., 2012;Madikizela et al., 2018). Toxoflavine induces cytotoxicity and cell death specifically in breast cancer cells (Wu et al., 2024). Its exposure results in chlorotic injury to panicles and restricts the development of both foliage and root systems in rice (Jeong et al., 2003).

In addition to the above, numerous other xenobiotics commonly used in pharmaceuticals and daily-use products have been identified in the soil sample of the study site. These compounds include O-Desmethyllevomepromazine, previously known as methotrimeprazine, which is a pharmaceutical used as an analgesic, antipsychotic, anxiolytic and sedative (O'Neill and Fountain, 1999). CAY10510 (prostaglandin F2α or PGF2α) is a pharmaceutical used in the treatment of glaucoma and eyelash hypotrichosis (Rahman et al., 2022). 15-oxo-18Z-tetracosenoic acid is a pharmaceutical-grade compound which is used in the management of demyelinating disorders and acquired immunodeficiency syndrome, as well as the prediction of mortality associated with cardiovascular diseases and chronic renal disease, Alzheimer's disease (AD) (Li et al., 2019). 2,2'-Bipyridylamine has highly photoprotective activity and tumour prevention properties (Schödel et al., 1996).13-Hydroxypergolide glucuronide, a derivative of Glucuronides, is the most important class of phase 2 xenobiotic metabolites and typically has a detoxifying role (Stachulski and Meng, 2013). Mebhydrolin is a potent antihistamine, this subgroup includes such frequently sold drugs as xylometazoline in the form of a 0.1% nasal spray; cromoglycic acid in the form of 2% eye drops (Prokopenko et al., 2021). Lipoxin is an anti-inflammatory compound (Batiha et al., 2022). Trandolaprilat is the biologically active form of trandolapril, a medication commonly prescribed for managing severe hypertension (Alfaro, Navarro-Retamal, and Caballero, 2020). 3'-N-Acetyl-4'-O-(14-

methylpentadecanoyl) fusarochromanone has antimalarial and anti-cancer activity, pharmacokinetic properties and therapeutic potential (Mahdavian et al., 2014; Watanabe et al., 2023).

Desmethylhalofantrine (Halofantrine) is an orally administered blood schizonticidal agent effective against both chloroquine-sensitive and chloroquine-resistant strains of Plasmodium, demonstrating significant antimalarial properties (Bryson and Goa, 1992). Haloperidol is commonly utilised in the management of delirium (Smit et al. 2023). O-Desmethylquinidine (6'-Hydroxycinchonine) is a newly reported metabolite of quinidine that has antiarrhythmic potency (Ueda and Nickols, 1980). N-(adamantan-1-yl)-1-(5-fluoropentyl)-1H-indole-3-carboxamide (STS-135), also referred to as 5F-APICA and 1-(cyclohexylmethyl)-1H-indole-3-carboxylic acid, 8-quinolinyl ester (BB-22), is a Synthetic cannabinoid (SC) which is used as a psychoactive substance (Ameen, Brown, and Dennany, 2022). 13,14-dihydro-15(R, S)-hydroxy-16,16-difluoro Prostaglandin E1-d4 (Prostaglandin El (PGE1, alprostadil)) is used in erectile failure (Porst, 1996). Low-dose ritonavir and lopinavir are combined to make the coformulatedlopinavir/ritonavir (Kaletra®), a boosted protease inhibitor (PI). It is used in combination with other antiretroviral drugs for the treatment of HIV infection in Lopinavir/ritonavir-based antiretroviral therapy (ART) (Oldfield and Plosker, 2006). Benoxinate or Benoxinate hydrochloride [2-(diethylamino) ethyl-4-amino-3-butoxybenzoate monohydrochloride; oxybuprocaine J is a local anaesthetic drug (Kasuya et al., 1987). Lamprolobine is used as the main active component of Compound Kushen injection (CKI) against a variety of cancers, including Breast cancer (Ye et al., 2022). Cl-amidine suppresses colitis and is used for the treatment of inflammatory bowel diseases (IBDs), mainly Crohn's disease and ulcerative colitis (Chumanevich et al., 2011). N-omega-propyl-L-Arginine (N^{ω}-propyl-l-arginine (20 mg/kg)) was found to block some of the behavioural and biochemical effects of phencyclidine, which is a useful pharmacological approach for the treatment of schizophrenia (Klamer et al., 2004). 3-Methyl-dodecanedioic acid is a type of dicarboxylic acid utilised in producing nylon, adhesives, powder coatings, paints, and corrosion inhibitors, all of which are commonly used in water treatment and the pulp and paper industry, chemical facilities and other industrial facilities (Bertuzzi et al., 2000). Carboxymethyloxysuccinate (NaCMOS) is a recently developed sequestering compound that functions as a builder in detergent formulations (Newsome and How, 1979).

Various studies show that plants can absorb and translocate these compounds to edible parts (Hu et al., 2010; Li et al., 2015; Madikizela et al., 2018), as evidenced by paracetamol accumulation in the edible portions of maize (Bartrons and Peñuelas, 2017; Hammad et al., 2018; Madikizela et al., 2018). In *E. horemanii*, xenobiotics tended to accumulate predominantly in leaves, whereas similar compounds in *E. crassipes* were observed to accumulate predominantly in roots (Pi et al., 2017). These pharmaceutical xenobiotics generate ROS through drug metabolism, leading to cellular damage. From vegetables, these xenobiotics may enter humans through dietary intake. In a study, 0.22 to 927 ng/g of pharmaceutical drug was reported in plants, indicating that consumption of edible parts of such plants will result in ingestion of approximately a single therapeutic dose of xenobiotic pharmaceuticals in humans (Dodgen et al., 2013; Madikizela et al., 2018). Future research must focus on the presence of these xenobiotics in various trophic levels, especially their bioaccumulation in plants from where they can enter other subsequent trophic levels. Therefore, in future, more focus should be directed on the occurrence and plant uptake of xenobiotics, the impact of xenobiotics on the morphology and physiology of the plants, as these could have the potential to cause more health hazards through biological magnification.

Conclusions

This study reveals the presence of xenobiotics in agricultural soils near the fertile land of Tons ecotone in Prayagraj, Uttar Pradesh, with 27 xenobiotic compounds spanning pharmaceuticals, pesticides, cosmeceuticals and corrosion inhibitors. Pharmaceuticals were the most prevalent, underscoring the growing impact of human activities and inadequate waste disposal practices. The presence of these diverse xenobiotics indicates significant contamination of agricultural land due to unsustainable human activities and improper disposal practices. The findings emphasise the critical need for evaluating the effect of these compounds on the flora and fauna found in contaminated areas, improved waste management strategies, stricter regulation of chemical usage, and enhanced monitoring of soil health in order to detect the extent of soil pollution. Given the potential for xenobiotic translocation into edible crops or their leaching in nearby water bodies, future research should focus on the long-term effects of these xenobiotics on various trophic levels of the ecosystem. Addressing these challenges is critical for safeguarding both environmental and public health.

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Author Contribution

Vaishali Trivedi: Research problem design, investigation, and analysis, writing of the manuscript. Dr. Anil Kumar Tewari: Analysis of data and review of the manuscript. Dr. Sanjay Kumar Mishra: Conceptualization of the work, review and editing of the manuscript.

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