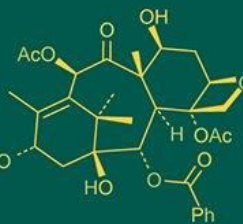
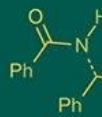
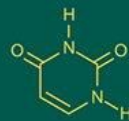
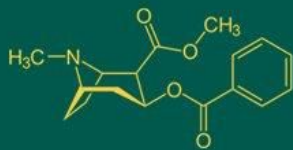


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Fate of triclosan in soil and sediment matrix: A comprehensive review and half-life assessment in sediment

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Abstract

Triclosan (TCS) is a widely utilized antimicrobial agent present in personal care products, household items, and medical applications. Due to its extensive use and the inefficiency of conventional wastewater treatment processes in completely removing it, TCS is frequently detected in wastewater effluents and sludge. Its subsequent accumulation in soil raises significant concerns regarding its persistence and potential environmental hazards. Beyond affecting soil microbial communities, TCS can also bioaccumulate in organisms, leading to toxic effects, thereby necessitating studies on its stability and degradation dynamics in various environmental matrices. In this study, a comprehensive literature review was conducted to examine the sources, occurrence, and environmental fate of TCS in soil systems. Additionally, an experimental study was performed under controlled aerobic laboratory conditions to determine the half-life of TCS in a sediment-water system. The degradation kinetics were assessed using a first-order kinetic model, revealing a half-life of 21.35 days, indicating the moderate persistence of TCS in soil. These findings highlight the potential risks associated with long-term contamination and underscore the need for improved remediation strategies. Advanced bioremediation techniques, such as bioaugmentation and the use of synthetic microbial consortia, are recommended to enhance TCS degradation efficiency and mitigate its environmental impact.

Keywords: Triclosan, occurrence, fate, half-life, microbial degradation

Introduction

Medicinal Triclosan (TCS, 5-chloro-2-(2,4-dichlorophenoxy) phenol) is a synthetic antimicrobial with antibiotic and antimycotic properties. It inhibits fatty acid synthesis by blocking enoyl reductase and shares structural similarities with toxic compounds like PCBs and dioxins [1]. Initially developed in the 1957, triclosan has been incorporated into a variety of consumer products, including soaps, toothpaste, deodorants, hand sanitizers, and cosmetics, due to its strong antibacterial and antifungal properties [2]. It is also found in certain plastics, textiles, and medical devices to prevent microbial contamination [3]. In the pharmaceutical industry, triclosan is used in some prescription mouthwashes and topical antiseptic around 0.1% to 0.3% (w/w), particularly for the treatment of gingivitis and skin infections [4]. One of the major concerns about triclosan is its frequent release into the environment. Since it is widely used in rinse-off personal care products, a large proportion of triclosan is washed down domestic wastewater and enters wastewater treatment plants. However, conventional wastewater treatment processes are often inefficient at completely removing triclosan but studies shows that advance wastewater treatment plants remove up to 99%, but its high sorption potential (log Kow value of 4.76) leads to accumulation in different environmental matrixes [5, 6]. Once in the environment, triclosan can undergo various chemical transformations, potentially forming even more toxic byproducts, such as chlorinated dioxins [3, 7]. Studies suggest that prolonged exposure to triclosan and its degradation product may contribute to the development of antibiotic-resistant bacteria, disrupting natural microbial communities [8, 9]. Furthermore, triclosan has been linked to endocrine disruption, as it can interfere with hormone regulation in humans and wildlife [7, 10-12]. Due to these concerns, regulatory agencies such as the U.S. Food and Drug Administration (FDA) and the European Union have imposed restrictions on its use in certain consumer products. Despite the 2016 FDA ban on triclosan in soaps, it remains in high market demand [13].

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Triclosan being a hydrophobic compound with moderate water solubility, meaning it has a strong tendency to bind to organic matter in the soil [12, 14]. This adsorption behavior affects its mobility, making it less likely to leach into groundwater (<1%) but increasing its persistence in surface environmental matrixes and can translocate to deeper layers [15]. Once triclosan released in to environment it can enter soil and sediment matrixes through multiple pathways, including direct absorption from water or the application of wastewater treatment sludge (biosolids) as agricultural fertilizer, irrigation with contaminated water, and direct disposal of triclosan-containing waste [16]. Additionally, industrial effluents and leaching from landfills contribute to triclosan contamination in terrestrial ecosystem [17]. In the U.S. alone, 5.6 million dry tons of biosolids are produced annually, with 60% applied to land. The fate of organic pollutants from biosolids remains uncertain and is determined by several factors, including its chemical properties, interactions with soil components, and environmental conditions. The persistence of triclosan in soil varies depending on the specific environmental conditions. Studies report triclosan's soil half-life as 18-58 days and 2.5-35 days, depending on factors such as temperature, soil type, aerobic or anaerobic conditions, microbial activity, and exposure to sunlight [15, 18, 19]. Several studies have reported that triclosan degradation is significantly slower under anaerobic condition leading to prolonged persistence [7, 12, 20].

Another important degradation pathway for triclosan in soil is photodegradation, particularly in surface soils exposed to sunlight. radiation from sun can break down triclosan into various transformation products, including polychlorinated phenols and dioxins. In a laboratory study Under artificial sunlight, TCS photodegraded in dried loamy sand with a half-life of 17 days, while degradation in deeper soil was limited due to light obstruction caused by upper layer [19]. Its photoproducts, 2,8-DCDD (2,8-dichlorodibenz-p-dioxins, a chlorinated dioxin) and 2,4-DCP (2,4-dichlorophenol, a priority EPA-regulated pollutant) increases the risk [21]. The long-term accumulation of triclosan in soil poses several ecological risks. It can disrupt soil microbial communities, affecting nutrient cycling and plant growth [8, 9]. Moreover, its persistence increases the likelihood of bioaccumulation in terrestrial food chains, with potential implications for human and animal health [12].

This study we reviewed source, occurrence, biotic and abiotic degradation mechanisms of triclosan in soil. Additionally, a laboratory experiment will measure triclosan's half-life in soil, using degradation kinetics models to track its persistence. Experimental results will be compared with existing literature to identify key factors affecting degradation. Understanding triclosan's environmental fate is crucial for addressing soil contamination, informing remediation strategies, and mitigating ecological risks associated with its widespread use.

Sources and Occurrence in Soil and Sediment

Although triclosan (TCS) is primarily considered a waterborne contaminant, it is also detected in soil within terrestrial environments. Its presence in soil and sediment matrices arises from multiple anthropogenic sources, mainly due to its extensive use in personal care products,

pharmaceuticals, and industrial applications [1, 7, 12]. While sediments can readily absorb TCS from contaminated water, industrial discharge, wastewater irrigation, and sludge application serve as the primary pathways for TCS contamination in soil [16]. These sources contribute to the accumulation and persistence of TCS in terrestrial environments, where it may undergo various degradation processes influenced by soil characteristics and environmental conditions. Understanding the fate and transformation of TCS in soil is essential for assessing its environmental risks and developing effective remediation strategies [1, 7, 12, 16]. Due to its effectiveness, triclosan (TCS) production increased from 1,500 tons in 1998 to 4,762 tons in 2015, peaking at 6,350 tons in 2011 [22, 23]. It is widely used in pharmaceuticals, personal care products, and household disinfectants, leading to its release into wastewater streams [6, 12]. Industrial effluents containing triclosan, if not properly treated, can contaminate nearby soil and water bodies, causing its accumulation in terrestrial ecosystems. This persistent pollutant can adsorb to soil particles, undergo transformation, or leach into groundwater, affecting microbial communities and ecological balance. Long-term exposure to triclosan in soil may alter degradation dynamics, influencing its persistence and potential risks to the environment. Understanding the fate of triclosan in soil is crucial for developing effective remediation strategies to mitigate its impact [12, 23].

Triclosan (TCS) is commonly detected in municipal wastewater due to its widespread use in household products such as soaps, toothpaste, and cosmetics. Studies have reported that TCS was present in 75% of liquid and 30% of bar soaps between 1999 and 2000, increasing to 93% in liquid, gel, or foam soaps from 2008 to 2010 [24, 25]. In Sweden, approximately 2 tons of TCS were used annually in toothpaste, with an additional 300 kg contributed by other personal care products [26].

Beyond personal hygiene, it is also incorporated into household goods such as kitchenware, dishwashing liquids, toys, computer equipment, furniture, humidifiers, helmets, wall coverings, air filters, blankets, mops, handrails, paints, earplugs, coolers, waterers, feeders, and vacuum food sealers [1]. The textile industry utilizes TCS in clothing, shoes, sandals, and towels to provide antimicrobial protection [27]. In the medical field, it is present in first aid products, including antiseptics, burn creams, night splints, and medicated sprays [1]. Office and school supplies such as calculators, scissors, paper, adhesives, cutting instruments, view binders, and pencils also contain TCS due to its antimicrobial properties [1]. Additionally, the food industry employs TCS in active food packaging materials and plastic crates to inhibit microbial contamination [7]. Given its extensive presence in everyday items, understanding its degradation and fate in the environment is crucial for evaluating its long-term ecological effects.

Despite wastewater treatment, residual triclosan persists in effluents. When treated or untreated wastewater is used for irrigation in agricultural fields, TCS accumulates in soil, potentially disrupting microbial communities and plant growth. Its persistence raises concerns about environmental contamination and antimicrobial resistance development. Triclosan undergoes degradation in soil through biotic (microbial) and abiotic (photodegradation, hydrolysis, and oxidation) pathways. However, factors such as soil type,

organic matter content, and environmental conditions influence its degradation rate and half-life. Understanding TCS degradation mechanisms and its persistence in soil is crucial for assessing its environmental impact.

Triclosan is frequently detected in municipal wastewater due to its presence in household products such as soaps, toothpaste, and cosmetics. Triclosan (TCS) is reported to be present in 75% of liquid and 30% of bar soaps (1999-2000) and in 93% of liquid, gel, or foam soaps (2008-2010) [24, 25]. In Sweden, 25% of toothpaste brands used 2 tons of TCS annually, with other personal care products contributing 300 kg [26]. Even after wastewater treatment, residual amounts of triclosan persist in effluents. When these treated or untreated wastewater effluents are used for irrigation in agricultural fields, triclosan can accumulate in soil, affecting microbial communities and plant growth.

Sewage sludge, commonly used as a soil amendment in agriculture, often contains high concentrations of triclosan. Activated sludge concentrations of TCS typically range from 580 to 14,700 µg/kg dry weight, while biosolids have been reported to contain between 90 and 32,900 µg/kg [28, 29]. Studies across three continents have documented median TCS concentrations in WWTP sludge at approximately 5000 µg/kg dry weight [14]. Moreover, WWTPs employing activated sludge treatment with anaerobic biosolid digestion retain approximately 50 ± 19% of the influent TCS mass in sewage sludge [28]. Soil samples from agricultural sites in Michigan amended with biosolids retained TCS concentrations of 0.55-3.5 nmol/kg over two years [30], while biosolids from three Michigan WWTPs contained 0.31-24.4 µmol/kg. In dewatered municipal biosolids, TCS concentrations reached 37.6 µmol/kg [31]. Additionally, studies have detected TCS in biosolid-amended soils 33 years after application [32]. The limited mobility of TCS in soil results in low groundwater contamination risk [30], but its presence in runoff and tile drainage water from biosolid-amended fields has been documented [33]. Triclosan (TCS) concentrations in freshwater sediments have been studied extensively across various countries. In Spain, Canosa *et al.* reported TCS levels at 35.7 ng/g, while Chen *et al.* found concentrations up to 4.32 ng/g in China [34, 35]. Juksu *et al.* documented significantly higher levels in Thailand at 726 ng/g [36]. Studies from India showed variable TCS concentrations, with Nag *et al.* reporting 5.11-50.36 ng/g and Ramaswamy *et al.* observing a range of 11-85.3 ng/g [37, 38]. In Nigeria, Afolabi *et al.* detected a much lower concentration of 0.056 ng/g. Pintado *et al.* reported a TCS level of 9.6 ng/g in Spain, while Zhao *et al.* identified the highest concentration at 1329 ng/g in China [39, 40].

In estuarine sediments, TCS levels also vary significantly. Miller *et al.* reported a concentration of 800 ng/g in the USA. In Spain, Agüera *et al.* found TCS concentrations ranging from 0.27 to 130.7 ng/g. These findings highlight the widespread presence and variable concentration of TCS in aquatic environments, influenced by factors such as geographical location, sediment characteristics, and local pollution sources. Long-term studies have confirmed the persistence of TCS in sediment cores from lakes and estuaries, indicating potential long-term environmental retention. These findings underscore the need for further research on TCS degradation kinetics, as its continued presence in biosolids and soil raises ecological and human health concerns [41].

Table 1: Occurrence of Triclosan in Soil and Sediment

Source	Sampling Source	Country	Detected level (min-max)	Reference
Sediment	Fresh water	Spain	35.7 ng/g	(34)
		China	Up to 4.32 ng/g	(35)
		Thailand	726 ng/g	(36)
		India	5.11-50.36 ng/g	(37)
		India	11-85.3 ng/g	(38)
		Nigeria	0.056ng/g	(42)
		Spain	9.6 ng/g	(39)
		China	1329 ng/g	(40)
	Estuarine	USA	800 ng/g	(43)
		Spain	0.27 to 130.7 µg/kg	(44)
Soil	Agricultural soil	USA	Up to 1.02 ng/g	(30)
		USA	331.6-552.6 nmol/kg	(45)

Fate of Triclosan in Soil and Sediment

Triclosan (TCS) degradation in soil primarily occurs through sorption and biodegradation mechanisms, with microbial activity playing a crucial role in its transformation. The degradation pathway of TCS in soil involves several key microbial processes. Upon release, TCS binds strongly to soil particles, particularly in the upper soil layers, due to its high partition coefficient [16] but has a higher mobility in alkaline soils due to the presence of its anionic form at high pH. Sorption strength affects bioavailability and degradation rates [46]. Triclosan leaches to deeper soil layers, but its primary degradation occurs in the upper 10 cm. Mobility is higher in sandy soils with low organic matter and cation exchange capacity (CEC) [15]. Over time, microbial communities within the soil metabolize TCS, breaking it down into transformation products. Microbial metabolism of TCS is mediated by specific bacterial strains, including *Pseudomonas*, *Sphingomonas*, and *Bacillus*, which utilize oxidative enzymes such as laccases, peroxidases, and oxygenases to initiate the breakdown process [13]. Soil microbes specially ammonia-oxidizing bacteria, facilitate the conversion of triclosan into Me-TCS, potentially as a defense mechanism against triclosan toxicity [47]. The primary degradation pathway begins with oxidation and hydroxylation of the triclosan molecule, followed by dechlorination and ring cleavage. The transformation products include methyl triclosan (Me-TCS), 2,4-dichlorophenol (2,4-DCP), and hydroquinone derivatives, which are further metabolized into simpler organic acids [13, 48].

However, accumulated TCS in soil can alter microbial diversity, potentially reducing its degradation efficiency and increasing the persistence of other co-existing xenobiotics [49]. In a study by Waria *et al.* initial analysis (up to 2 weeks) detected only TCS, with no metabolites. By week 3, a new peak identified as Me-TCS appeared in biotic treatments, indicating microbial transformation. This process continued for up to 18 weeks, with Me-TCS persisting in biotic soils but absent in inhibited treatments, confirming its biological origin [50]. Triclosan degradation is influenced by various abiotic and biotic factors, including soil temperature, moisture, pH, organic matter, and microbial activity. Aerobic biodegradation is the primary pathway, while anaerobic conditions, especially in winter, slow down the process due to limited oxygen diffusion [51]. While Me-TCS is stable under aerobic conditions, under anaerobic conditions, it may undergo O-demethylation and dehalogenation, similar to 2,4,6-trichloroanisole, before complete mineralization [52].

The microbes induced biodegradation of triclosan (TCS) in soil primarily occurs through meta-cleavage, ortho-cleavage, and unclassified degradation pathways. The meta-cleavage pathway begins with a regioselective dioxygenase attack at the 2,3-position of TCS, forming dihydroxy-TCS, which further degrades to monohydroxy-TCS^[53]. This pathway ultimately leads to the production of 2,4-dichlorophenol, which undergoes ring-opening and dechlorination, allowing its integration into the tricarboxylic acid (TCA) cycle for complete mineralization^[54]. In contrast, the ortho-cleavage pathway converts TCS into 2,4-dichlorophenol and 3-chloro-cis, cis-muconate, which are further broken down into phenol and catechol before complete mineralization^[55]. Some microorganisms, such as *Dyella* sp. WW1, introduce hydroxyl radicals into the benzene ring through monooxygenase or dioxygenase activity, leading to dechlorination^[56, 57]. Additional studies have identified alternative TCS degradation mechanisms. *Providencia rettgeri* MB-IIT utilizes biomethylation and dechlorination, leading to complete mineralization (Balakrishnan & Mohan, 2021). The strain's laccase enzyme (LAC) facilitates C-C bond cleavage, producing low molecular weight carboxylic acids. Overall, TCS degradation occurs primarily through oxygenation and dechlorination, with variations in microbial pathways depending on species. Further studies using advanced methods are necessary to elucidate intermediate metabolites and predict degradation mechanisms for newly isolated TCS-degrading microbes.

Degradation kinetics and Half-life

Triclosan (TCS) degradation in soil varies significantly depending on soil type, environmental conditions, and the presence of oxygen. Ying *et al.* reported a half-life of 18 days for TCS in a loam soil under aerobic conditions in laboratory studies, whereas no degradation was observed in oxygen-deprived soils^[19]. Similarly, McAvoy *et al.* found that TCS is primarily degraded under aerobic conditions, while it remains persistent in anaerobic environments^[16]. Studies have reported a broad range of degradation half-lives. In laboratory incubation experiments, Waria *et al.* observed half-lives of 78 days in silty clay loam and 421 days in fine sand soils, suggesting that soil texture plays a crucial role in TCS persistence^[50]. Lozano *et al.* reported a half-life of 107 days in field conditions, while Xu *et al.* found degradation ranging from 13.1 to 32.5 days^[29, 58]. Additional laboratory studies have reported half-lives between 2.5 and 35 days^[14]. Some reports suggest an even longer half-life of 540 days in soil^[59], raising concerns about its persistence in the environment.

The application of biosolids influences TCS degradation. Al-Rajab *et al.* demonstrated that TCS mineralization increases when applied with liquid biosolids compared to direct addition, particularly when compared with dewatered biosolids^[60]. However, TCS has been detected in biosolid-amended soils even 33 years after application^[32], indicating long-term persistence. Additionally, Gottschall *et al.* detected TCS in soil a year after biosolid application, raising concerns about its potential for environmental recirculation and bioaccumulation^[31]. TCS's high partition coefficient ($K_{oc} = 9200$) and resistance to hydrolysis contribute to its persistence in soil^[61]. The antimicrobial also has a low transport potential from biosolids into surface runoff^[62], further influencing its fate in soil ecosystems.

Experimental case Study: Half-Life of Triclosan in Sediment

Materials and Methods

Chemicals and reagents

Triclosan ($C_{12}H_7Cl_3O_2$; 5-chloro-2-(2,4-dichlorophenoxy) phenol, CAS 3380-34-5) with 97% purity (HPLC grade) was obtained from Sigma-Aldrich, India. Solid-phase extraction cartridges were sourced from Sigma-Aldrich, USA. Chromatographic-grade solvents, including methanol (CAS 67-56-1), acetonitrile (CAS 75-05-8), and orthophosphoric acid (CAS 7664-38-2), were purchased from Sisco Research Laboratories, Mumbai. Neutral Borosil glassware ensured chemical purity. Analytical-grade reagents from Sigma, SRL, HI-media, and Merck were used to maintain experimental accuracy and reliability. These high-purity chemicals and materials ensured precision in sample preparation, extraction, and analysis throughout the study.

Equipment and laboratory wares

A UV-Vis detector-based HPLC system (Analytical, India) was used for triclosan separation and quantification. Additional instruments included refrigerated centrifuge (REMI, India), electronic balance (OHAUS, USA), thermostatic water bath (ESCY, USA), tabletop centrifuge 5430 (Eppendorf, Germany), incubator (Wadigarfl, India), digital pH meter (LABINDIA, India), microwave oven (Kenstar, India), mercury thermometer (G H ZEAL, England), and micropipettes (Eppendorf, Germany).

Extraction of test chemical from water sediment sample

Triclosan was extracted from aqueous samples using solid-phase extraction (SPE) with Supel Select HLB 60 mg/3 mL cartridges. Water samples were centrifuged at 6,500 rpm for 10 minutes, and 30 mL of supernatant was collected. The SPE cartridges were conditioned with methanol, distilled water, and 0.01 M HCl, then loaded with the samples. After washing and drying, triclosan was eluted with acetonitrile-methanol (1:1), evaporated to dryness, and reconstituted in the mobile phase for HPLC analysis, ensuring precise quantification of triclosan in experimental samples.

Triclosan quantification followed Nag *et al.* with modifications^[37]. Ten grams of sediment were extracted with 50 mL ethyl acetate, agitated for 2 hours, and sonicated for 15 minutes. After centrifugation at 6500 rpm (10 min), the supernatant was filtered (0.45 μ m nylon filter), evaporated, and reconstituted in the mobile phase for HPLC analysis.

Quantification of test chemical

Triclosan was quantified using HPLC with a UV-Vis detector and a C18 ODS-BP column (250 mm $\times$ 4.6 mm, 5 μ m). Isocratic separation used a 4:1 acetonitrile-water mobile phase (pH 2.5, orthophosphoric acid). The flow rate was 1.5 mL/min, with a 20 μ L injection volume, 35°C column temperature, and 280 nm detection wavelength.

Experimental media preparation

A 200 ppm Triclosan stock solution was prepared by dissolving 0.2 g of Triclosan in 20 mL of 0.01 M sodium hydroxide (NaOH) and adjusting the volume to one liter with distilled water. For sediment exposure, pond sediment sourced from ICAR-CIFE, Mumbai, was air-dried, powdered, sieved through a 2 mm mesh, and spiked to the

desired concentration. The sediment was characterized as loam (sand: 52.13%, silt: 36.25%, clay: 11.63%) using the international pipetting method (Gee and Or, 2002), with an organic carbon content of 1.06%, determined by the Walkley and Black method (1934). To spike, 30 kg of sediment was mixed with the appropriate volume of Triclosan stock solution, allowed to equilibrate in darkness for four days for uniform distribution before use in the experiment.

Experimental Setup

A controlled laboratory experiment was conducted to assess the degradation kinetics and stability of triclosan (TCS) in sediment under aerobic conditions. A total of 100 g of sediment was spiked with a calculated volume of TCS stock solution to achieve a target concentration of 1 mg/kg. The sediment was then transferred into 1000ml glass container, with 300 ml of water added to maintain a 1:3 sediment-to-water ratio, ensuring appropriate environmental conditions for microbial activity and degradation processes.

To monitor the degradation of TCS over time, sediment samples were systematically collected at specific intervals: 0, 1, 2, 4, 8, 16, and 32 days post-spiking. The experiment was conducted under controlled aeration to simulate aerobic environmental conditions that are essential for microbial degradation. Samples were analyzed using standardised protocol.

The degradation kinetics of TCS were evaluated using a first-order degradation model as described by Huang *et al.* (2014) [20]:

$$c_t = c_0 \times e^{-kt}$$

where C_0 represents the initial concentration of TCS, C_t is the concentration at time t , and k is the degradation rate constant. The half-life ($t_{1/2}$) was derived using the equation:

$$t_{1/2} = \ln(2) / k$$

The results from this experiment provide valuable insights into TCS persistence in sedimentary environments, which is crucial for environmental risk assessment and pollution management strategies.

The detailed experimental protocols, instruments and software etc. used in the study should be described here with their proper references. The details of the study area should also be provided.

Statistical analysis

All statistical analyses were performed using Microsoft Excel 2023 and SPSS version 25. Descriptive statistics, and hypothesis testing were conducted to assess data variability and significance. Appropriate statistical tests were applied based on data distribution and experimental design, ensuring rigorous evaluation of results with a significance level set at $p < 0.05$.

Results and Discussion

Preparation of standard curve of triclosan in HPLC

A standard curve for triclosan (TCS) was prepared using freshly prepared standard concentrations of 0, 1, 2, 4, 8, and 10 $\mu\text{g/mL}$. These standards were transferred to HPLC sample vials and analyzed using a previously standardized HPLC procedure. Chromatographic analysis provided distinct peak areas for each TCS concentration, which were plotted to generate the standard curve.

Figure 1 illustrates the retention time and peak areas corresponding to different TCS concentrations, while Figure 2 presents the standard curve, demonstrating the linear relationship between peak area and TCS concentration. Linear regression analysis yielded an R^2 value of 0.9929, indicating an excellent correlation and ensuring the accuracy of the method for TCS quantification. This validated curve provides a reliable reference for determining unknown triclosan concentrations in environmental samples, ensuring precise measurement in degradation studies.

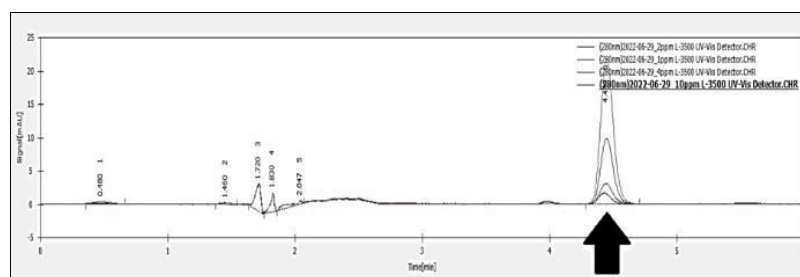


Fig 1: Chromatogram of triclosan at different concentration indicating retention time.

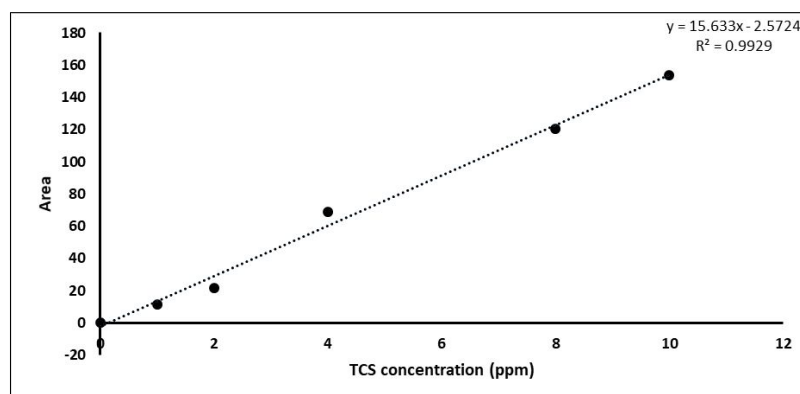


Fig 2: Standard curve of triclosan at different concentrations viz 0, 1, 2, 4, and 10 mg/L

Study of recovery rate in water, sediment

Before starting the experiment, the standardized method for triclosan recovery in water and sediment was evaluated. Various concentrations were spiked, and recovery rates were measured to assess the method's accuracy and reliability.

The recovery percentages of triclosan from spiked water samples demonstrated high precision and consistency. At a spiked concentration of 0.1 mg/L, the average recovery was 98.254%, while at 0.2 mg/L, it was 98.693%. For 0.5 mg/L, the recovery was 98.314%, and at 1 mg/L, it was 98.644%. Higher concentrations, such as 5 mg/L and 10 mg/L, showed recoveries of 99.005% and 98.600%, respectively (Table 2). These results confirm the robustness and reliability of the method for water samples.

For sediment samples, the recovery efficiency varied with spiking concentrations (Table 6). At the lowest spike level of 0.1 mg/kg, the measured concentration was 0.071 ± 0.002 mg/kg, resulting in a recovery of 70.99%. With an increased spike of 0.2 mg/kg, the recovery rose to 78.56%, with a measured concentration of 0.157 ± 0.003 mg/kg. At 0.5 mg/kg, the measured concentration was 0.420 ± 0.005 mg/kg, the recovery was 83.958%, and at 1 mg/kg, it was 85.663%.

mg/kg, yielding a recovery of 83.96%. When spiked at 1 mg/kg, the recovery further increased to 85.66%, corresponding to a measured concentration of 0.857 ± 0.013 mg/kg. At 2 mg/kg, the recovery was 87.80%, with a measured concentration of 1.756 ± 0.012 mg/kg. Higher spiking levels of 5 mg/kg and 10 mg/kg resulted in recoveries of 90.09% and 94.38%, with measured concentrations of 4.504 ± 0.011 mg/kg and 9.439 ± 0.067 mg/kg, respectively (Table 3).

Table 2: Recovery rate of triclosan from spiked water

Spiked (mg/L)	Measured (mg/L)	Average recovery (in percentage)
0.1	0.095 ± 0.034	94.710
0.2	0.196 ± 0.014	97.940
0.5	0.490 ± 0.036	98.100
1	0.986 ± 0.078	98.644
2	1.9777 ± 0.214	98.835
5	4.950 ± 0.385	99.005
10	9.860 ± 0.509	98.600

*Data represented as mean $\pm$ SD (n=3)

Table 3: Recovery rate of triclosan from spiked sediment

Spiked (mg/kg)	Measured (mg/kg)	Average recovery (in percentage)
0.1	0.071 ± 0.002	70.99
0.2	0.157 ± 0.003	78.556
0.5	0.420 ± 0.005	83.958
1	0.857 ± 0.013	85.663
2	1.756 ± 0.012	87.8
5	4.504 ± 0.011	90.085
10	9.439 ± 0.067	94.385

*Data represented as mean $\pm$ SD (n=3)

TCS degradation in sediment and half-life calculation

The fluctuation of triclosan (TCS) concentrations in the water-sediment system throughout the experiment is depicted in Figure 3. At the start, TCS levels in the water phase were undetectable using High-Performance Liquid Chromatography (HPLC). However, as time progressed, detectable amounts appeared in the aqueous phase, peaking on the fourth day. After reaching this maximum, concentrations gradually decreased until they were no longer detectable. In sediment, an initial recovery rate of 84.64% (n=6) was recorded immediately after spiking.

Significant differences ($p < 0.05$) in TCS concentrations between water and sediment were observed throughout the study, highlighting its shifting distribution. Using a first-order kinetic model, the estimated half-life of TCS in sediment was 21.52 days, indicating moderate persistence. This suggests that TCS remains in sediment for a considerable period, raising concerns about potential environmental risks. The observed fluctuations and degradation rate offer valuable insights into TCS behavior in aquatic ecosystems, reinforcing the importance of continued environmental monitoring.

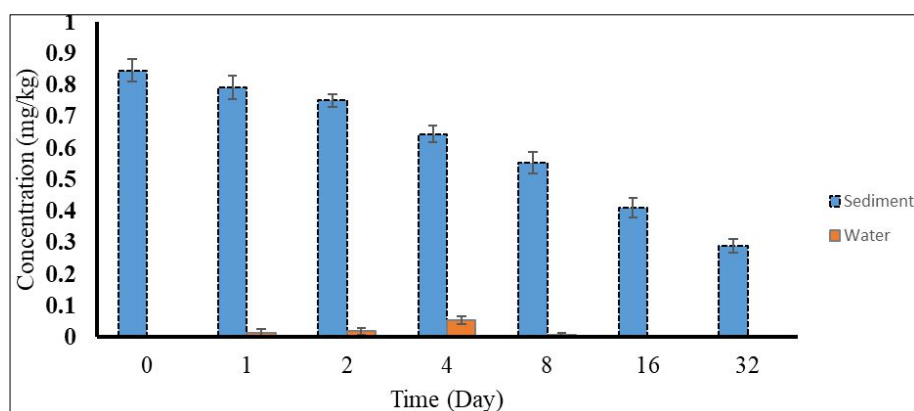


Fig 3: Degradation of TCS in Sediment-water system over time

Understanding how triclosan (TCS) behaves in aquatic environments is essential for evaluating its potential effects on aquatic life. Research has shown that the movement and persistence of triclosan in sediment-water systems largely

depend on the physical and chemical characteristics of both media [18]. Examining how triclosan degrades, binds to sediments, and is released back into the water is critical to assessing its environmental impact. This study monitored

triclosan concentrations in water and sediment to better understand its stability and interactions. Initially, triclosan was undetectable in water, likely because only the sediment was spiked with the compound, leading to minimal release into the water column. However, as time progressed, triclosan gradually diffused from sediment into water, peaking on the fourth day before decreasing. These fluctuations highlight triclosan's variable behavior in sediment, with notable changes observed across sampling intervals. The estimated half-life of triclosan in sediment was found to be 21.52 days, closely aligning with Ying *et al.*, who reported an 18-day half-life in loam soil under aerobic conditions ^[51]. Meanwhile, Huang *et al.* determined that triclosan's half-life in water-sediment systems ranged between 32 and 62 days, influenced by organic carbon levels, microbial populations, and sediment composition ^[20]. Biological degradation, including microbial breakdown and methylation, plays a major role in triclosan dissipation. Additional studies have found that the half-life of TCS ranges from 55 to 239 days, with higher persistence in sediments that exhibit strong adsorption capacity ^[63].

Conclusion

This study reviewed the occurrence, fate, and degradation pathways of triclosan (TCS) in soil, along with an experimental investigation of its half-life under controlled aerobic conditions. TCS primarily enters soil through wastewater effluents, sludge application, and agricultural irrigation with contaminated water. While wastewater treatment plants partially degrade TCS, residual amounts persist in soil, where microbial metabolism and abiotic processes influence its breakdown. Aerobic conditions promote degradation via oxidative and reductive pathways, forming metabolites like methyl triclosan and 2,4-dichlorophenol, whereas anaerobic conditions lead to prolonged persistence. The experimental study determined a half-life of 21.35 days under aerobic conditions, aligning with reported values of 18 to 421 days, depending on soil properties. These findings highlight TCS's persistence, potential bioaccumulation in biota, and long-term contamination risks. Further research is needed to develop effective remediation strategies to mitigate its environmental impact and protect soil ecosystems.

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Conflict of Interest

The authors declare no conflict of interest related to this work.

References

1. Dhillon G, Kaur S, Pulicharla R, Brar S, Cledón M, Verma M, *et al.* Triclosan: Current Status, Occurrence, Environmental Risks and Bioaccumulation Potential. *IJERPH*. 2015 May 22;12(5):5657-84.
2. Macri D. Worldwide use of triclosan: Can dentistry do without this antimicrobial? *Contemp Clin Dent*. 2017;8(1):7.
3. Bedoux G, Roig B, Thomas O, Dupont V, Le Bot B. Occurrence and toxicity of antimicrobial triclosan and by-products in the environment. *Environ Sci Pollut Res*. 2011 Nov 5;19(4):1044-65.
4. McBain AJ, Rickard AH, Gilbert P. Possible implications of biocide accumulation in the environment on the prevalence of bacterial antibiotic resistance. *J Ind Microbiol Biotechnol*. 2002 Dec 1;29(6):326-30.
5. Bock M, Lyndall J, Barber T, Fuchsman P, Perruchon E, Capdevielle M. Probabilistic application of a fugacity model to predict triclosan fate during wastewater treatment. *Integr Environ Assess Manag*. 2010 Jul 1;6(3):393-404.
6. Ogunyoku TA, Young TM. Removal of triclocarban and triclosan during municipal biosolid production. *Water Environ Res*. 2014 Mar;86(3):197-203.
7. Dar OI, Aslam R, Pan D, Sharma S, Andotra M, Kaur A, *et al.* Source, bioaccumulation, degradability and toxicity of triclosan in aquatic environments: A review. *Environ Technol Innov*. 2022 Feb;25:102122.
8. Karmakar S, Abraham TJ, Kumar S, Kumar S, Shukla SP, Roy U, *et al.* Triclosan exposure induces varying extent of reversible antimicrobial resistance in *Aeromonas hydrophila* and *Edwardsiella tarda*. *Ecotoxicol Environ Saf*. 2019 Sep;180:309-16.
9. Varghese P, Kumar K, Sarkar P, Karmakar S, Shukla SP, Kumar S, *et al.* Impact of Triclosan on Bacterial Biodiversity and Sediment Enzymes - A Microcosm Study. *Bull Environ Contam Toxicol*. 2024 Nov;113(5):59.
10. Bera KK, Kumar S, Paul T, Prasad KP, Shukla SP, Kumar K. Triclosan induces immunosuppression and reduces survivability of striped catfish *Pangasianodon hypophthalmus* during the challenge to a fish pathogenic bacterium *Edwardsiella tarda*. *Environ Res*. 2020 Jul;186:109575.
11. Hemalatha D, Nataraj B, Rangasamy B, Shobana C, Ramesh M. DNA damage and physiological responses in an Indian major carp *Labeo rohita* exposed to an antimicrobial agent triclosan. *Fish Physiol Biochem*. 2019 Jun 20;45(4):1463-84.
12. Kumar S, Paul T, Shukla SP, Kumar K, Karmakar S, Bera KK, *et al.* Biomarkers-based assessment of triclosan toxicity in aquatic environment: A mechanistic review. *Environ Pollut*. 2021 Oct;286:117569.
13. Yin Y, Wu H, Jiang Z, Jiang J, Lu Z. Degradation of Triclosan in the Water Environment by Microorganisms: A Review. *Microorganisms*. 2022 Aug 25;10(9):1713.
14. Reiss R, Mackay N, Habig C, Griffin J. An ecological risk assessment for triclosan in lotic systems following discharge from wastewater treatment plants in the United States. *Environ Toxicol Chem*. 2002 Nov 1;21(11):2483-92.
15. Butler E, Whelan MJ, Sakrabani R, Van Egmond R. Fate of triclosan in field soils receiving sewage sludge. *Environ Pollut*. 2012 Aug;167:101-9.
16. McAvoy DC, Schatowitz B, Jacob M, Hauk A, Eckhoff WS. Measurement of triclosan in wastewater treatment systems. *Environ Toxicol Chem*. 2002;21(7):1323-9.
17. Von Der Ohe PC, Schmitt-Jansen M, Slobodnik J, Brack W. Triclosan—the forgotten priority substance? *Environ Sci Pollut Res*. 2012 Feb;19(2):585-91.

18. Wu W, Hu Y, Guo Q, Yan J, Chen Y, Cheng J. Sorption/desorption behavior of triclosan in sediment-water-rhamnolipid systems: Effects of pH, ionic strength, and DOM. *J Hazard Mater.* 2015 Oct;297:59-65.
19. Ying GG, Yu XY, Kookana RS. Biological degradation of triclocarban and triclosan in a soil under aerobic and anaerobic conditions and comparison with environmental fate modelling. *Environ Pollut.* 2007;150(3):300-5.
20. Huang X, Wu C, Xiong X, Zhang K, Liu J. Partitioning and Degradation of Triclosan and Formation of Methyl-Triclosan in Water-Sediment Systems. *Water Air Soil Pollut.* 2014 Aug 9;225(9).
21. Chen L, Hu X, Cai T, Yang Y, Zhao R, Liu C, *et al.* Degradation of Triclosan in soils by thermally activated persulfate under conditions representative of in situ chemical oxidation (ISCO). *Chem Eng J.* 2019 Aug;369:344-52.
22. Bester K. Fate of Triclosan and Triclosan-Methyl in Sewage Treatment Plants and Surface Waters. *Arch Environ Contam Toxicol.* 2005 Jul;49(1):9-17.
23. Weatherly LM, Gosse JA. Triclosan exposure, transformation, and human health effects. *J Toxicol Environ Health B Crit Rev.* 2017 Nov 17;20(8):447-69.
24. Perencevich E, Wong M, Harris A. National and regional assessment of the antibacterial soap market: A step toward determining the impact of prevalent antibacterial soaps. *Am J Infect Control.* 2001 Oct;29(5):281-3.
25. USFDA. Safety and effectiveness of consumer antiseptics; tropical antimicrobial drug products for over-the-counter human use; proposed amendment of the tentative final monograph [Internet]. 2013. Available from: <https://www.govinfo.gov/content/pkg/FR-2013-12-17/pdf/2013-29814.pdf>
26. Adolfsson-Erici M, Pettersson M, Parkkonen J, Sturve J. Triclosan, a commonly used bactericide found in human milk and in the aquatic environment in Sweden. *Chemosphere.* 2002 Mar;46(9-10):1485-9.
27. Zhao C, Xie H, Xu J, Zhang J, Liang S, Hao J, *et al.* Removal mechanisms and plant species selection by bioaccumulative factors in surface flow constructed wetlands (CWs): In the case of triclosan. *Sci Total Environ.* 2016;547:9-16.
28. Chalew TE, Halden RU. Environmental exposure of aquatic and terrestrial biota to triclosan and triclocarban 1. *JAWRA J Am Water Resour Assoc.* 2009;45(1):4-13.
29. Lozano N, Rice CP, Ramirez M, Torrents A. Fate of triclosan in agricultural soils after biosolid applications. *Chemosphere.* 2010;78(6):760-6.
30. Cha J, Cupples AM. Detection of the antimicrobials triclocarban and triclosan in agricultural soils following land application of municipal biosolids. *Water Res.* 2009;43(9):2522-30.
31. Gottschall N, Topp E, Metcalfe C, Edwards M, Payne M, Kleywegt S, *et al.* Pharmaceutical and personal care products in groundwater, subsurface drainage, soil, and wheat grain, following a high single application of municipal biosolids to a field. *Chemosphere.* 2012;87(2):194-203.
32. Xia K, Hundal LS, Kumar K, Armbrust K, Cox AE, Granato TC. Triclocarban, triclosan, polybrominated diphenyl ethers, and 4-nonylphenol in biosolids and in soil receiving 33-year biosolids application. *Environ Toxicol Chem.* 2010;29(3):597-605.
33. Lapen D, Topp E, Metcalfe C, Li H, Edwards M, Gottschall N, *et al.* Pharmaceutical and personal care products in tile drainage following land application of municipal biosolids. *Sci Total Environ.* 2008;399(1-3):50-65.
34. Canosa P, Morales S, Rodriguez I, Rubi E, Cela R, Gómez M. Aquatic degradation of triclosan and formation of toxic chlorophenols in presence of low concentrations of free chlorine. *Anal Bioanal Chem.* 2005;383:1119-26.
35. Chen ZF, Wen HB, Dai X, Yan SC, Zhang H, Chen YY, *et al.* Contamination and risk profiles of triclosan and triclocarban in sediments from a less urbanized region in China. *J Hazard Mater.* 2018;357:376-83.
36. Juksu K, Zhao JL, Liu YS, Yao L, Sarin C, Sreesai S, *et al.* Occurrence, fate and risk assessment of biocides in wastewater treatment plants and aquatic environments in Thailand. *Sci Total Environ.* 2019 Nov;690:1110-9.
37. Nag SK, Das Sarkar S, Manna SK. Triclosan - an antibacterial compound in water, sediment and fish of River Gomti, India. *Int J Environ Health Res.* 2018 Jun 20;28(5):461-70.
38. Ramaswamy BR, Shanmugam G, Velu G, Rengarajan B, Larsson DJ. GC-MS analysis and ecotoxicological risk assessment of triclosan, carbamazepine and parabens in Indian rivers. *J Hazard Mater.* 2011;186(2-3):1586-93.
39. Pintado-Herrera MG, González-Mazo E, Lara-Martín PA. Determining the distribution of triclosan and methyl triclosan in estuarine settings. *Chemosphere.* 2014;95:478-85.
40. Zhao JL, Zhang QQ, Chen F, Wang L, Ying GG, Liu YS, *et al.* Evaluation of triclosan and triclocarban at river basin scale using monitoring and modeling tools: Implications for controlling of urban domestic sewage discharge. *Water Res.* 2013 Jan;47(1):395-405.
41. Bedoux G, Roig B, Thomas O, Dupont V, Le Bot B. Occurrence and toxicity of antimicrobial triclosan and by-products in the environment. *Environ Sci Pollut Res.* 2012;19:1044-65.
42. Afolabi F, Adeyinka GC, Adebisi GA. Evaluation and distribution of selected polychlorinated biphenyl congeners and triclosan in soil, sediment and surface water system: a case study of Ojutu River, Osun State, Nigeria. *Soil Sediment Contam.* 2023;32(3):287-304.
43. Miller TR, Heidler J, Chillrud SN, DeLaquil A, Ritchie JC, Mihalic JN, *et al.* Fate of triclosan and evidence for reductive dechlorination of triclocarban in estuarine sediments. *Environ Sci Technol.* 2008 Jun 15;42(12):4570-6.
44. Agüera A, Fernández-Alba AR, Piedra L, Mézcua M, Gómez MJ. Evaluation of triclosan and biphenylol in marine sediments and urban wastewaters by pressurized liquid extraction and solid phase extraction followed by gas chromatography mass spectrometry and liquid chromatography mass spectrometry. *Anal Chim Acta.* 2003;480(2):193-205.

45. Kinney CA, Furlong ET, Kolpin DW, Burkhardt MR, Zaugg SD, Werner SL, *et al.* Bioaccumulation of pharmaceuticals and other anthropogenic waste indicators in earthworms from agricultural soil amended with biosolid or swine manure. *Environ Sci Technol.* 2008 Mar 1;42(6):1863-70.
46. Lyndall J, Fuchsman P, Bock M, Barber T, Lauren D, Leigh K, *et al.* Probabilistic risk evaluation for triclosan in surface water, sediments, and aquatic biota tissues. *Integr Environ Assess Manag.* 2010.
47. Roh H, Subramanya N, Zhao F, Yu CP, Sandt J, Chu KH. Biodegradation potential of wastewater micropollutants by ammonia-oxidizing bacteria. *Chemosphere.* 2009;77(8):1084-9.
48. Lindström A, Buerge IJ, Poiger T, Bergqvist PA, Müller MD, Buser HR. Occurrence and environmental behavior of the bactericide triclosan and its methyl derivative in surface waters and in wastewater. *Environ Sci Technol.* 2002;36(11):2322-9.
49. Sverningsen H, Henriksen T, Priemé A, Johnsen AR. Triclosan affects the microbial community in simulated sewage-drain-field soil and slows down xenobiotic degradation. *Environ Pollut.* 2011;159(6):1599-605.
50. Waria M, O'Connor GA, Toor GS. Biodegradation of triclosan in biosolids-amended soils. *Environ Toxicol Chem.* 2011 Sep 23;30(11):2488-96.
51. Ying GG, Yu XY, Kookana RS. Biological degradation of triclocarban and triclosan in a soil under aerobic and anaerobic conditions and comparison with environmental fate modelling. *Environ Pollut.* 2007 Dec;150(3):300-5.
52. Goswami M, Recio E, Campoy S, Martín JF, Coque JJR. Environmental significance of O-demethylation of chloroanisoles by soil bacterial isolates as a mechanism that improves the overall biodegradation of chlorophenols. *Environ Microbiol.* 2007;9(10):2512-21.
53. Pfeifer F, Trüper HG, Klein J, Schacht S. Degradation of diphenylether by *Pseudomonas cepacia* Et4: enzymatic release of phenol from 2,3-dihydroxydiphenylether. *Arch Microbiol.* 1993;159:323-9.
54. Zhao F, Rezenom YH, Russell DH, Chu KH, others. Biodegradation of triclosan by a wastewater microorganism. *Water Res.* 2012;46(13):4226-34.
55. Kumari R, Ghosh Sachan S. Bioconversion of toxic micropollutant triclosan to 2,4-dichlorophenol using a wastewater isolate *Pseudomonas aeruginosa* KS2002. *Int J Environ Sci Technol.* 2019;16:7663-72.
56. Wang S, Yin Y, Wang J. Microbial degradation of triclosan by a novel strain of *Dyella* sp. *Appl Microbiol Biotechnol.* 2018;102:1997-2006.
57. Balakrishnan P, Mohan S. Treatment of triclosan through enhanced microbial biodegradation. *J Hazard Mater.* 2021;420:126430.
58. Xu J, Chen W, Wu L, Green R, Chang AC. Leachability of some emerging contaminants in reclaimed municipal wastewater-irrigated turf grass fields. *Environ Toxicol Chem.* 2009;28(9):1842-50.
59. Halden RU, Paull DH. Co-occurrence of triclocarban and triclosan in U.S. water resources. *Environ Sci Technol.* 2005 Mar 1;39(6):1420-6.
60. Al-Rajab AJ, Sabourin L, Scott A, Lapen DR, Topp E. Impact of biosolids on the persistence and dissipation pathways of triclosan and triclocarban in an agricultural soil. *Sci Total Environ.* 2009;407(23):5978-85.
61. Angin I, Yaganoglu A. Application of sewage sludge as a soil physical and chemical amendment. *Ekoloji.* 2009;19(73).
62. Sabourin L, Beck A, Duenk PW, Kleywegt S, Lapen DR, Li H, *et al.* Runoff of pharmaceuticals and personal care products following application of dewatered municipal biosolids to an agricultural field. *Sci Total Environ.* 2009;407(16):4596-604.
63. Huang X, Wu C, Hu H, Yu Y, Liu J. Sorption and degradation of triclosan in sediments and its effect on microbes. *Ecotoxicol Environ Saf.* 2015 Jun;116:76-83.