Biological Warriors: The Fight to Decompose Triclosan

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ABSTRACT

Humans are exposed to diverse emerging environmental pollutants in their everyday lives. Triclosan, an emerging pollutant in aquatic environments, has garnered significant attention for its potential detrimental impacts on aquatic ecosystems, particularly in the wake of the COVID-19 pandemic. Triclosan serves as a common antibacterial and antifungal agent found extensively in personal care items like toothpaste, soaps, and hand sanitizers. The primary origin of triclosan in aquatic settings is attributed to wastewater, stemming from its excessive utilization and disposal. Due to insufficient elimination at wastewater treatment facilities, triclosan residues ultimately infiltrate surface water and, potentially, groundwater. As one of the most concerned emerging pollutants, TCS received attention in its biological remediation research. Biodegradation plays a crucial role in the treatment of triclosan in wastewater, and it offers several advantages over physicochemical methods. Microorganisms, including bacteria, algae, and fungi, participate in the breakdown of triclosan through diverse metabolic routes, facilitating its transformation into less harmful compounds. Consequently, microbial degradation of TCS is considered a more dependable and advantageous remediation approach compared to other methods.

INTRODUCTION

Triclosan (TCS) (5-chloro-2-(2',4'-dichlorophenoxy) phenol) is used in various consumer products, including pharmaceuticals and personal care products (PPCPs) as well as bodywash, detergents, and cosmetics at concentrations ranging from 0.1% to 0.3% by weight due to its antibacterial properties (Nandikes *et al.,* 2022). The widespread use of triclosan leads to an increase in the level of TCS in environmental matrices, especially during the COVID-19 period. TCS, a synthetic chlorinated aromatic compound, is depicted in Figure 1. The primary contributor to TCS presence in aquatic ecosystems is wastewater discharge. Due to its widespread use, a substantial amount of TCS is washed down drains, ultimately entering wastewater treatment plants (WWTPs). WWTPs can achieve relatively high removal efficiencies for TCS, often exceeding 90% (Lee, 2015); trace amounts of TCS can still be detected in the effluent at concentrations up to µg/L. Consequently, TCS finds its way into water bodies through discharge and has been detected in surface water, groundwater, sediments, drinking water, wastewater, soils, and biosolids. Triclosan released into the environment can undergo various chemical, photochemical, and biological transformations, leading to the formation of more toxic by-products such as methyl TCS (MTCS), chlorinated TCS derivatives (CTDs), polychlorodibenzo-p-dioxins (PCDDs), chlorophenol derivatives (CPs), and chloroform. Due to its ubiquitous occurrence and environmental toxicity, it has raised potential risks to public health and ecosystems. A range of physical and chemical remediation techniques have been employed to tackle the removal of TCS from the environment. These methods include photolysis, UV irradiation, ozonation, sorption, advanced oxidation processes, adsorption, and oxidation. Biodegradation has been recognized as a viable and alternative method for the removal of TCS from the environment. Several microorganisms, comprising algae, fungi, bacterial consortia, and activated sludge, have been documented to participate in the biodegradation process of TCS. Compared to chemical and physical degradation methods, biological treatment is considered environmentally sustainable, which leads to the mineralization of organic contaminants without generating toxic by-products. Numerous bacterial species, including *Pseudomonas putida* and *Sphingomonas sp.*, exhibit the capability to biodegrade the hazardous TCS compound. Additionally, fungal species such as *Pleurotus ostreatus* and *Trametes versicolor* are recognized for their effectiveness in degrading TCS. Moreover, the algal strain Nannochloris sp. has demonstrated nearly complete TCS degradation through biosorption. These species possess enzymes that enable them to break down TCS into less harmful compounds, such as 2,4-dichlorophenol.

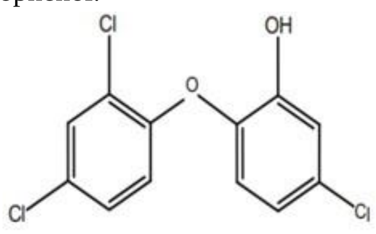

Fig 1. Structure of Triclosan

Adverse effects of TCS on aquatic organisms

TCS has been reported to cause adverse effects on aquatic organisms (Figure 2). TCS can enter the bodies of fish via the gills during respiration or through the ingestion of food, potentially leading to biomagnification in the food chain. Consequently, its concentrations tend to escalate as it progresses up the trophic levels. Triclosan shows adverse effects on reproduction and leads to developmental abnormalities in fish, affecting the growth and health of juvenile individuals. It also interferes with the action of thyroid hormones in amphibians. The toxicity of TCS can vary across different life stages of species.

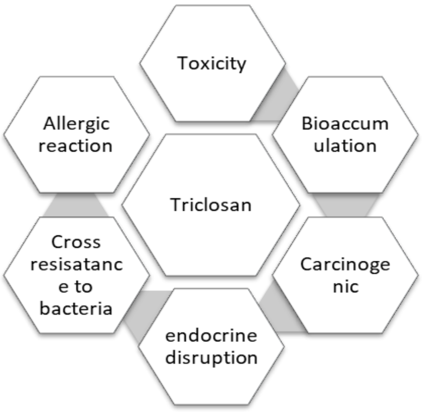

Fig 2. Toxicity of TCS

Treatment Technologies for Triclosan Removal

Removing TCS from the environment mainly includes Physical, chemical, biological, and combined methods (Figure 3).

Physical and chemical methods

While physical and chemical methods prove effective in removing TCS, they come with drawbacks, such as high construction costs and the potential formation of toxic by-products. However, various sorbents, including kaolinite and montmorillonite, have demonstrated effective triclosan removal capabilities. In addition, activated carbon (granular or powdered), graphene, biochar, carbon nanotubes, and kaolinite have also shown effectiveness in adsorbing TCS. A variety of chemical oxidation processes have proven effective in eliminating triclosan, including the UV/hydrogen peroxide-advanced oxidation process, UV irradiation, ozonation, and chlorination. Ozonation, for instance, can swiftly oxidize triclosan during wastewater treatment. UV irradiation boasts a removal efficiency of 93% in wastewater. Additionally, advanced membrane technologies such as nanofiltration (NF) and reverse osmosis (RO) membranes, along with advanced oxidation processes (AOPs) like UV/hydrogen peroxide, have demonstrated high efficacy in TCS removal.

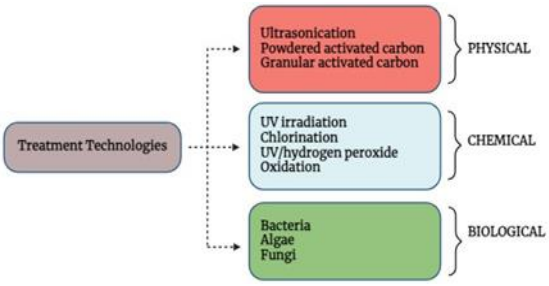

Fig 3. Treatment Technologies for Triclosan Removal

Biological methods

Biological removal refers to the removal of TCS by various biological processes such as plants, fungi, algae, or bacteria through absorption, accumulation, or biotransformation.

Biodegradation by bacteria

A multitude of microbial species have demonstrated efficacy in TCS degradation, such as soil bacteria like *Pseudomonas putida* TriRY and *Alcaligenes xylosoxidans* subsp. *denitrificans* TR1, which utilizes triclosan as the sole carbon source for degradation. Additionally, bacteria such as *Sphingopyxis sp.* KCY1, *Dyella sp.*, *Sphingomonas sp.* RD1, *Sphingomonas sp.* PH-07, and *Sphingomonas sp.* YL-JM2C, along with ammonia-oxidizing bacterium (AOB) *Nitrosomonas europaea*, produces dioxygenase enzymes, while YL-JM2C bacteria produce chlorohydroquinone dehalogenase. These enzymes play crucial roles in cleaving or modifying the molecular structure of TCS, rendering it more susceptible to further breakdown.

Biological degradation mechanism in bacteria

Most of the TCS-degrading bacteria degrade TCS mostly under aerobic conditions. However, different TCS-degrading microorganisms exhibit varying degrees of degradation abilities. The meta-cleavage pathway is one of the pathways through which certain bacteria can metabolize TCS. The process commences with the initial assault by a regioselective dioxygenase enzyme, specifically targeting the 2,3-position of TCS. This action introduces oxygen into the molecule, yielding dihydroxy-TCS as a result. Subsequently, dihydroxy-TCS undergoes transformation to monohydroxy-TCS through an ether-bond cleavage facilitated by the 2,3-dioxygenase enzyme, ultimately producing 2,4-dichlorophenol (2,4 DCP). The enzyme chlorohydroquinone dehalogenase catalyzes the dehalogenation of 2,4-dichlorophenol, resulting in the conversion into 2-chlorohydroquinone. The compound 2-chlorohydroquinone can undergo further transformations, leading to the formation of hydroquinone, which is a less chlorinated compound. Further degradation steps result in the formation of carbon dioxide, water, and other unchlorinated by-products. Bacteria utilize the ortho-cleavage pathway alongside the meta-cleavage pathway as an alternative route. Intermediate metabolites generated from processes such as ether bond cleavage and dechlorination can be converted into low molecular weight carboxylic acids, which are subsequently metabolized into simpler compounds. TCS degradation often involves oxygenation reactions leading to the opening of the aromatic ring and dechlorination processes, which help transform toxic intermediates into less harmful forms. The metabolic pathways involved in the degradation of TCS vary among different microbial strains.

Biodegradation by algae

Algae possess the ability to absorb TCS from their surrounding water environment, thereby playing a crucial role in both the removal and detoxification of triclosan. Once taken up, TCS can accumulate within the algal cells. Cell walls and exopolysaccharides function as a barrier in the bioaccumulation process. The microalgal cell wall possesses similarities to pectin, hemicellulose, arabinogalactan protein, cellulase, and lignin. Due to the presence of various functional groups, the cell walls of microalgae carry a net negative charge, including carboxyl (COOH), amine (NH_2), and phosphoryl (PO_4) groups (Oruganti *et al.*, 2022). The bio-adsorption of contaminants can occur owing to the existence of cationic groups on the surface of microalgal cells. This process is facilitated by electrostatic interactions between the cationic groups on the cell surface and the anionic or polar functional groups found in the contaminants. Once inside the cells, microalgae employ intracellular biodegradation mechanisms to break down and metabolize contaminants. Cytochrome P450 enzymes play a crucial role in the metabolism and detoxification of xenobiotic compounds, encompassing pharmaceuticals and environmental pollutants. These enzymes catalyze the transformation of xenobiotic compounds into either less toxic forms or more readily excretable from the body. Photodegradation is another mechanism utilized by microalgae to degrade contaminants. In this process, light, sunlight, or artificial light sources play a crucial role in initiating chemical reactions that lead to the breakdown of compounds. The removal of triclosan by common freshwater microalgae includes *Chlorella pyrenoidosa*, *Desmodesmus sp., and Scenedesmus obliquus.*

Biological degradation mechanism in algae

The degradation of PPCPs by algae can involve various mechanisms, including biosorption, bioaccumulation, biodegradation, photodegradation, and volatilization. Microalgae converts complex parent compounds into simpler compounds. The degradation can occur through two main mechanisms: metabolic degradation and co-metabolism. Co-metabolism is a biological process whereby microalgae metabolize contaminants by adding other chemicals or substances. The additional organic matter may act as a carbon source to promote microalgae growth, or it may cause the microalgae to release enzymes that break down contaminants, or both. The breakdown of micropollutants by microalgae can be divided into three steps: 1) rapid adsorption, 2) transference of molecules, and 3) bioaccumulation, biodegradation, or both (Figure 4).

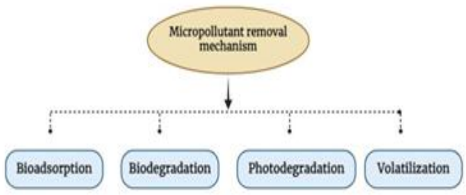

Fig 4. Mechanisms involve in micropollutant removal

The degradation of TCS by algae involves a series of enzymatic reactions, each contributing to the transformation of the compound into simpler and often less toxic substances such as hydrogenation, dehydroxylation, dehydrogenation, carboxylation, decarboxylation, hydroxylation, oxidation, hydrolysis, reduction, ring cleavage, demethylation, and glycosylation. Metabolites formed during microbial degradation are categorized into phase I and phase II reactions, representing different enzymatic transformations. Phase I reactions involve hydrolysis and dechlorination, while phase II reactions consist of xylosylation, methylation, and glycosylation. Phase I metabolites include 2,4-dichlorophenol, dichlorohydroxydiphenyl ether, glucosyl, and pentosyl conjugates, while phase II reactions produce additional metabolites. These compounds undergo successive transformations, including glucosylation, methoxylation, pentosylation, and dechlorination, ultimately forming less toxic, unchlorinated conjugates. However, the precise mechanisms of further degradation remain elusive. Microbial degradation processes facilitate the transformation of 2,4-dichlorophenol into hydroquinone and other unchlorinated compounds, which pose reduced harm to the soil.

CONCLUSION

The present article gives insight into how triclosan-containing wastewater causes severe health-related issues and depletes the stability of the ecosystem, emphasizing the critical need for effective treatment methods. Bacterial and microalgae-based treatment is superior to conventional methods. Algal-bacterial systems hold significant promise for sustainable water treatment. These systems leverage the synergistic relationship between algae and bacteria to efficiently remove contaminants from water while promoting environmental sustainability. Moreover, limited research has been carried out regarding the interaction of TCS with algal-bacterial consortia.

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