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Photocatalytic Degradation of Psychiatric Pharmaceuticals in Hospital WWTP Secondary Effluents Using g-C_3N_4 and g-C_3N_4/MoS_2 Catalysts in Laboratory-Scale Pilot

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Abstract: Today, the pollution caused by a multitude of pharmaceuticals used by humans has been recognized as a major environmental problem. The objective of this study was to evaluate and compare the photocatalytic degradation of ten target psychiatric drugs in hospital wastewater effluents using g-C_3N_4 and 1%MoS_2/g-C_3N_4 (1MSCN) as photocatalytic materials. The experiments were performed using real wastewater samples collected from hospital wastewater treatment plant (WWTP) secondary effluent in spiked and inherent pharmaceutical concentration levels. The photocatalytic experiments were performed in a laboratory-scale pilot plant composed of a stainless-steel lamp reactor (46 L) equipped with ten UVA lamps and quartz filters connected in series with a polypropylene recirculation tank (55–100 L). In addition, experiments were carried out in a solar simulator apparatus Atlas Suntest XLS+ at a 500 Wm^{-2} irradiation intensity. The analysis of the samples was accomplished by solid-phase extraction, followed by liquid chromatography-Orbitrap high-resolution mass spectrometry. Results showed that the photocatalytic degradation of pharmaceutical compounds followed first-order kinetics. In all cases, 1MSCN presented higher photocatalytic performance than g-C_3N_4. The removal rates of the pharmaceutical compounds were determined above 30% and 54% using g-C_3N_4 and 1MSCN, respectively. Parallel to kinetic studies, the transformation products (TPs) generated during the treatment were investigated.

Keywords: pharmaceuticals; psychiatric drugs; hospital wastewaters; solar photocatalysis; g-C_3N_4; 1MoS_2/g-C_3N_4; transformation products

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1. Introduction

One of the emerging concerns in environmental science is the occurrence of pharmaceuticals and their metabolites in the environment. Pharmaceutical compounds are regarded as frustrating compounds, as they are released into the environment continuously from various scattered points [1], due to the large amounts of medical compounds, human and veterinary, that are consumed each year [2,3]. Pharmaceuticals are designed with high stability and can maintain their chemical form long enough to be retained in the human body and to remain in the environment in their original structure [4]. Pharmaceutical compounds reach waters with concentrations from ng L^{-1} to μg L^{-1}, but even at these very low concentrations, they can cause toxicological risk to living organisms due to their chemical and physical properties [2,3,5,6].

The appearance of mental health problems is associated with many social and economic determinants, such as poverty, deprivation, and inequalities. Given that there is an increase in these factors in times of economic crisis, it is to be expected that the mental health of the population is also at higher risk. According to the World Health Organization, the COVID-19 pandemic has also created a global mental health crisis, undermining the mental health of millions of people, although even before it, one in eight people worldwide

were already living with a mental disorder [7]. There has been special interest in psychiatric drugs, as contaminants, because of their continuously increasing use, on the one hand, and because many of them affect phylogenetically conserved neuroendocrine systems, on the other hand, which may create problems to other non-target organisms. The rapid increase in the use of psychiatric drugs has resulted in their strong presence in the environment. As to their therapeutic use, psychiatric drugs are categorized into six classes: (i) anxiolytics, hypnotics, and sedatives; (ii) antidepressants; (iii) stimulants; (iv) antipsychotics; (v) mood stabilizers; (vi) drugs to treat drug dependence [8].

The psychiatric drugs enter the wastewater treatment plants from the disposal of unused or expired medicines and from human excretions. Although psychiatric drugs are excreted by humans mainly as metabolites, biologically active or not, part of the drug is excreted without being metabolized. Hospital and municipal WWTPs represent the major source for the presence of this class of micropollutants in the environment due to their limited capacity to remove such micropollutants [2,9].

Pharmaceuticals may have diverse consequences on the environment, as these compounds can be persistent, bioaccumulative, and can cause both serious and chronic human and ecotoxicological harm. The presence of psychiatric drugs in water reservoirs worldwide, as well as with their potential bioaccumulation in aquatic organisms, has been confirmed in several studies. For instance, in hospital WWTP effluent of Ioannina (northwestern Greece), venlafaxine has been detected with a maximum mean concentration of 550.3 ngL^{-1} and bupropion with a minimum mean concentration of 39.9 ngL^{-1} [9]. In addition, in a monitoring study of psychiatric drugs in rivers of Portugal, the most frequent psychiatric drugs found were antidepressants such as carbamazepine, citalopram, fluoxetine, sertraline, and trazodone in concentrations of up to 2.0 ng L^{-1} [10]. Moreover, Vasskog et al. reported sertraline detection in wastewater treatment plants in Norway at concentrations ranging from 0.9 to 6.3 ngL^{-1} [11]. The drugs used in neurology and psychiatry affect humans as well as every other living organism. Telles-Correia et al. found that venlafaxine, bupropion, quetiapine, and other pharmaceuticals cause severe liver diseases [12]. Antidepressants are considered toxic to very toxic to algae [13]. In addition, Grzesiuk et al. (2018) demonstrated that, upon chronic exposure to low concentrations, fluoxetine affected the ecophysiology of two species of microalgae, *Acutodesmus obliquus* and *Nannochloropsis limnetica* [14]. Finally, Best et al. (2014) demonstrated that Venlafaxine at environmentally relevant concentrations affects the metabolic capacities and may compromise the adaptive responses of rainbow trout to an acute stressor [15].

Another important issue to be considered is the production of transformation products (TPs) under environmental conditions or during wastewater treatment. TPs are products generated in the environment and in the wastewater treatment plants by chemical, physical, and biological processes. Some studies have noticed the presence of TPs in different environmental matrices, including wastewaters, surface waters, and soil. The mostly unknown ecotoxicological effects of TPs can affect human health and aquatic biota [16].

Different methods, such as adsorption, and biological and chemical processes such as chlorination have been used for water treatment and environmental protection. These methods have shown limited success and usually do not reach complete removal of pharmaceutical compounds, so more powerful and efficient technologies are required for application in treatment of pharmaceuticals. On the other hand, Advanced Oxidation Processes (AOPs) are promising, modern, and environmentally friendly methods used to remove organic pollutants, such as pharmaceutical compounds, prior to discharge into aquatic systems [3,17]. AOPs can attain better quality of treated water as they improve overall removal efficiencies of contaminants [18]. Among AOPs, heterogeneous photocatalysis using semiconductors has proven to be a promising technique due to its high efficiency, photostability, and non-toxic properties of the catalysts.

Graphitic carbon nitride (g-C_3N_4) has semiconductor characteristics with a narrow band gap of ~2.7 eV. g-C_3N_4 expedited interest as a non-toxic, environmentally friendly, thermally and chemically stable, and facilely available inexpensive material, due to low-

cost precursors (e.g., urea, thiourea, and melamine), for a broad variety of photocatalytic applications [19,20]. However, its photocatalytic efficiency is limited because of the recombination process, which consists of the transport of electrons back to the valence band. This phenomenon competes with the electron–hole pair formation, which diminishes the efficiency of the pollutant degradation. To circumvent this problem, several strategies have been established by different research groups. One approach is to combine two or more semiconductors. Heterostructuring can separate the electrons and holes and change their band structures, decreasing the recombination effects. Molybdenum sulfide (MoS_2) has also attracted great attention as a co-catalyst as it possesses a narrow band gap (1.2–1.9 eV), high stability, and proper band edge potential for the interfacial charge transfer in heterostructures [21]. The coupling of MoS_2 and g-C_3N_4 could significantly reduce the charge carrier recombination and highly improve photocatalytic activity compared to bare materials.

This study focuses on the application of photocatalysis for the removal of psychiatric drugs present in HWW secondary effluents at spiked and inherent concentrations by different photocatalytic semiconductors and different irradiation sources. g-C_3N_4 and 1MSCN were compared for the photocatalytic degradation of target compounds. According to our knowledge, photocatalytic degradation of psychiatric drugs by g-C_3N_4 and 1MSCN in real hospital WWTP secondary effluents and environmentally relevant concentrations has not yet been published in the scientific literature. Experiments have also been performed in order to investigate the influence of different irradiation types (UV and simulated solar radiation) on the process performance as a limited number of articles deal with the comparison among the commonly used light sources.

2. Results and Discussion

2.1. Degradation of Psychiatric Drugs

The efficiency of photocatalysts g-C_3N_4 and 1MSCN in the photocatalytic degradation of the target compounds was investigated in two photocatalytic systems, a small lab-scale reactor and solar simulator (suntest), as well as lab-scale pilot plant (L-PP) and UV-lamps. The degradation of the psychiatric drugs followed first-order kinetics in both cases. Tables 1 and 2 show the photocatalytic degradation rate constants, correlation coefficients, and % removal of the target compounds, while Figure 1 shows the degradation kinetics.

Table 1. Kinetic parameters (first-order kinetic constants (k, min^{-1}), correlation coefficients (R^2), and % degradation of pharmaceuticals) after photocatalytic treatment at the solar simulator.

	g-C_3N_4			1MSCN		
Pharmaceutical	**k (min^{-1})**	**R^2**	**% Degradation (Time, min)**	**k (min^{-1})**	**R^2**	**% Degradation (Time, min)**
Amisulpride	0.029	0.9944	100 (240)	0.03	0.9901	100 (180)
O-desmethyl-venlafaxine	0.012	0.9394	98 (300)	0.013	0.9728	99 (300)
Venlafaxine	0.015	0.9989	99 (300)	0.015	0.9791	99 (300)
Clozapine	0.003	0.9814	60 (300)	0.003	0.9699	66 (360)
Citalopram	0.002	0.9882	53 (300)	0.003	0.9594	62 (300)
Quetiapine	0.015	0.99	99 (300)	0.04	0.9926	99 (120)
Carbamazepine	0.009	0.9677	96 (300)	0.012	0.9836	97 (300)
Bupropion	0.004	0.9772	76 (300)	0.004	0.9476	79 (360)
Fluoxetine	0.017	0.9771	99 (300)	0.02	0.9934	100 (300)
Amitriptyline	0.001	0.9265	30 (300)	0.002	0.9915	54 (300)

As can be seen in Figure 1, photocatalytic degradation of target compounds using 1MoS_2/g-C_3N_4 proceeded faster than the g-C_3N_4 photocatalyst in all experiments. Photocatalytic degradation experiments at the lab-scale pilot plant using 1MSCN showed removal percentages at the end of the process that ranged between 91% and 100%. Namely, in the presence of 1MSCN, after 360 min, photocatalytic removal by 100% for amisulpride,

venlafaxine, and metabolite O-desmethyl venlafaxine and 99% for quetiapine, fluoxetine, carbamazepine, and amitriptyline were accomplished; while for clozapine, citalopram, and bupropion, 98%, 97%, and 91% were recorded, respectively. On the other hand, the degradation efficiency of target compounds differed to a lesser extent in the presence of g-C_3N_4 (78–100%). Using g-C_3N_4 as a photocatalyst, the lowest degradation performance of 78% was recorded in the case of bupropion. Amitriptyline showed the highest degradation rate constant in both experiments (0.039 min^{-1} and 0.025 min^{-1} for 1MoS_2/g-C_3N_4 and g-C_3N_4, respectively). The 1MSCN photocatalyst showed a higher photocatalytic degradation of the psychiatric drugs also in experiments carried out at the solar simulator apparatus. Amisulpride, fluoxetine, and metabolite O-desmethyl venlafaxine were completely degraded. Using g-C_3N_4, the photocatalytic efficiency decreased by 6% and 9% for clozapine and citalopram, respectively. The lowest degradation performances of 54% and 30% were recorded for amitriptyline in the case of 1MSCN and g-C_3N_4, respectively.

Regarding the influence of different types of irradiation sources on the efficiency of psychiatric drugs removal, lab-scale pilot plant experiments using 1MSCN photocatalyst led to higher photocatalytic rate constants by 3.45% (for citalopram) and 56% (for amitriptyline) compared to the efficiency of g-C_3N_4 photocatalyst. In the case of simulated solar simulator experiments, the photocatalytic process led to the complete degradation of amisulpride, metabolite O-desmethyl venlafaxine, fluoxetine, and quetiapine. Using 1MSCN photocatalyst instead of g-C_3N_4 photocatalyst, the rate constants increased by 3.45% for amisulpride and metabolite O-desmethyl venlafaxine, 17.65% for fluoxetine, and 166.7% for quetiapine.

For comparison to previously reported results dealing with the degradation of psychoactive pharmaceuticals using g-C_3N_4 photocatalysts, Kane et al. [22] studied the degradation of carbamazepine under UV light irradiation using g-C_3N_4 and g-C_3N_4/TiO_2 photocatalysts, reporting that composite materials possess higher degradation activity. More specifically, removal percentages were 71.41% and 5.97% for 10% g-C_3N_4/TiO_2 and g-C_3N_4, respectively. In addition, Moreira et al. [23] studied the photocatalytic degradation of nine organic pollutants (including three psychiatric drugs, namely carbamazepine, venlafaxine, and fluoxetine) found in biologically treated effluents of an urban wastewater treatment plant (North Portugal) using exfoliated g-C_3N_4. At the end of the photocatalytic process, an almost complete removal of all compounds was observed.

Table 2. Kinetic parameters (rate constants (k, min^{-1}), correlation coefficients (R^2), and % degradation of pharmaceuticals) after photocatalytic treatment at laboratory pilot plant.

	g-C_3N_4			**1MoS_2/g-C_3N_4**		
Pharmaceutical	**k (min^{-1})**	**R^2**	**% Degradation (Time, min)**	**k (min^{-1})**	**R^2**	**% Degradation (Time, min)**
Amisulpride	0.017	0.9958	100 (360)	0.018	0.9028	100 (360)
O-desmethyl-venlafaxine	0.009	0.9831	97 (360)	0.009	0.9259	100 (360)
Venlafaxine	0.014	0.9837	100 (360)	0.016	0.9956	100 (360)
Clozapine	0.01	0.9786	98 (360)	0.011	0.9892	98 (360)
Citalopram	0.007	0.9371	93 (360)	0.008	0.9669	97 (360)
Quetiapine	0.015	0.9915	99 (360)	0.02	0.9953	99 (240)
Carbamazepine	0.013	0.9877	99 (360)	0.015	0.9922	99 (360)
Bupropion	0.004	0.9751	78 (360)	0.005	0.9772	91 (360)
Fluoxetine	0.011	0.9869	99 (360)	0.011	0.9894	99 (360)
Amitriptyline	0.025	0.9945	99 (180)	0.039	0.9961	99 (120)

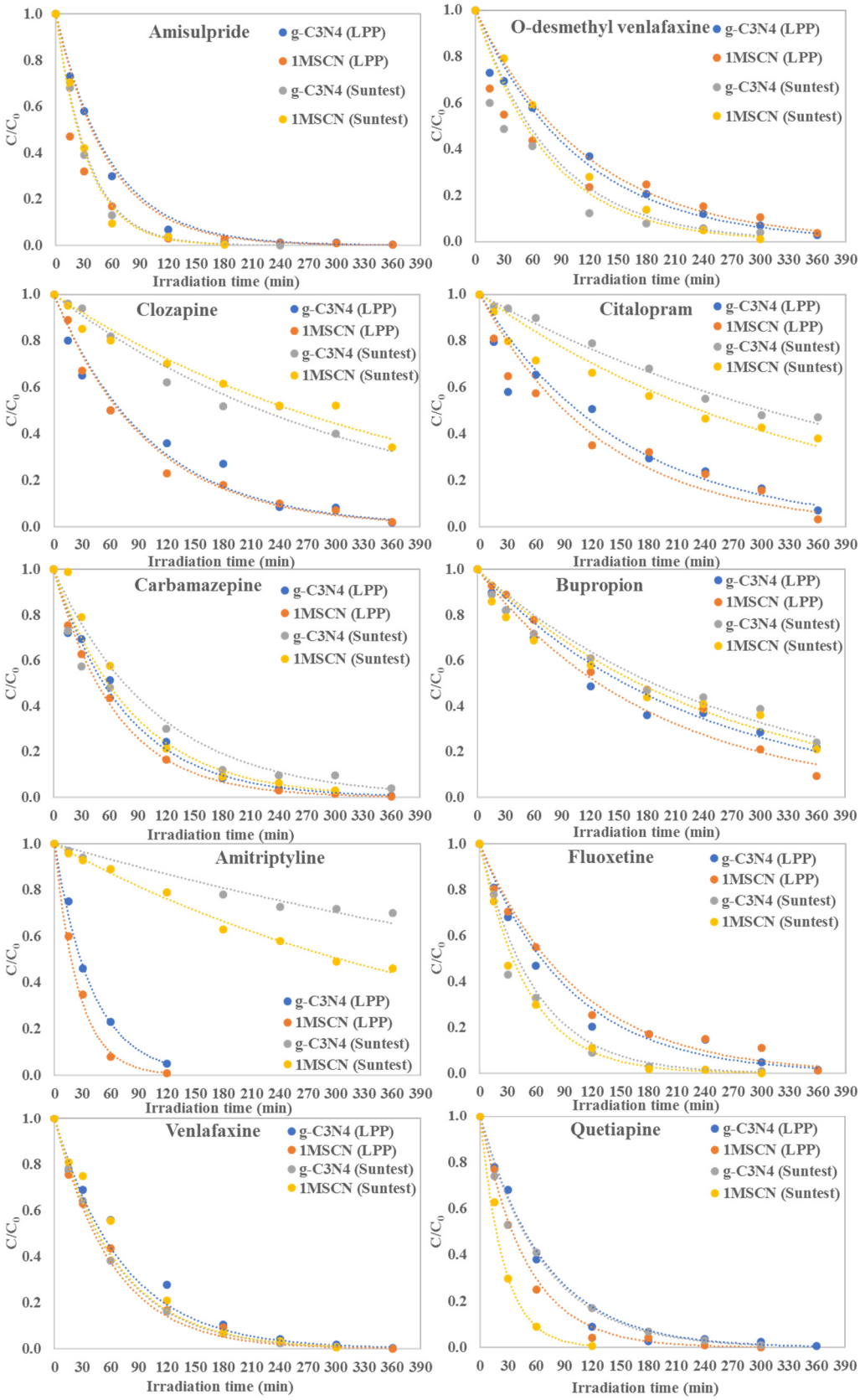


Figure 1. Photocatalytic degradation of psychiatric drugs using g-C_3N_4 and 1MoS_2/g-C_3N_4 catalysts in lab-scale pilot plant (LPP) and in solar simulator (Suntest) as a function of irradiation time.

The occurrence and photocatalytic removal of the inherent concentration of target psychiatrics in the effluent using g-C_3N_4 and 1MSCN photocatalysts (100 mgL^{-1}) under simulated solar radiation were also determined. As we are dealing with the inherent concentration of pharmaceutical compounds, the presence of all ten psychiatric drugs was not detected in every case. More specifically, using g-C_3N_4, a total of five compounds (amisulpride, venlafaxine, O-desmethyl venlafaxine, and quetiapine) were detected in concentrations higher than LOQ, while fluoxetine was found in trace levels. Amisulpride's concentration in the effluent was 42.2 ngL^{-1}. Venlafaxine and metabolite O-desmethyl venlafaxine was found at concentrations levels of 24.6 ngL^{-1} and 38.1 ngL^{-1}, respectively. Quetiapine presented the lowest observed concentration at 8.2 ngL^{-1}. After 120 min, amisulpride presented 44% degradation, while venlafaxine and metabolite O-desmethyl venlafaxine presented 43% and 37% elimination, respectively. The highest degradation rate, 85%, was noticed for quetiapine after 60 min of irradiation. Amisulpride, venlafaxine, O-desmethyl venlafaxine, carbamazepine, and fluoxetine were also found when 1MSCN photocatalyst was used. Concentrations ranging between 5.04 ngL^{-1} for fluoxetine and 578.5 ngL^{-1} for amisulpride. Amisulpride presented the highest degradation rate, 99%, after 180 min of irradiation, while the lowest degradation rate was noticed for fluoxetine, 47%, after 300 min of irradiation. At the end of the photocatalytic reaction (after 300 min), venlafaxine presented 97% degradation, while O-desmethyl venlafaxine and carbamazepine presented 90% and 80% degradation, respectively.

Additionally, BOD_5 and COD measurements were performed before and after the photocatalytic treatment at the lab-scale pilot plant using g-C_3N_4 and 1MSCN. The BOD_5/COD ratio is considered to be a suitable criterion for biodegradability, as it is not affected by the amount or the oxidation state of organic matter [24–26]. Table 3 shows the BOD_5, COD, and BOD_5/COD ratio measured in secondary effluent of hospital WWTP and after the photocatalytic processes. The ratio of BOD_5/COD after 360 min of irradiation time decreased from the initial 0.55 to 0.38 for g-C_3N_4 and 0.13 to 0.07 for 1MSCN. The variation in COD before and after the photocatalytic treatment may also be affected by the initial suspended solid concentrations in the treated effluents or the interference of produced H_2O_2 from the catalysts during the treatment.

Table 3. BOD_5 (mgL^{-1}), COD (mgL^{-1}), and BOD_5/COD measured in secondary effluent of hospital WWTP before and after photocatalytic treatment.

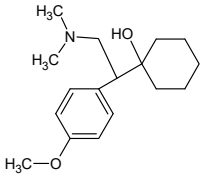
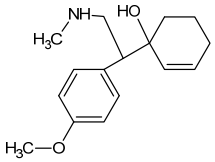
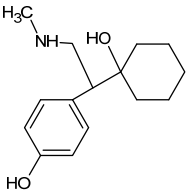
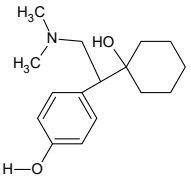
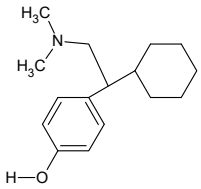
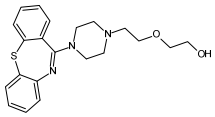
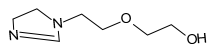
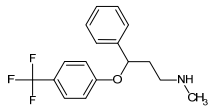
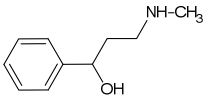
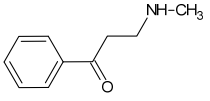
	g-C_3N_4		**1MoS_2/g-C_3N_4**	
	Before Treatment (t = 0 min)	**After Treatment (t = 360 min)**	**Before Treatment (t = 0 min)**	**After Treatment (t = 360 min)**
BOD_5 (mgL^{-1})	15.5	14	4.3	1.4
COD (mgL^{-1})	28	37	33	19
BOD_5/COD	0.55	0.38	0.13	0.07

2.2. Transformation Products

Most studies dealing with the treatment of real wastewaters examined usually only the removal of parent drug compounds, whereas our study coped with the challenge to identify transformation products at very low concentration in spiked and unspiked real effluent samples. LC–HRMS data on the identification of target psychiatric compounds TPs as well as their structures are summarized in Table 4. Figure 2 presents the evolution profiles of the identified transformation products after the photocatalytic process at the laboratory-scale pilot plant using 1MSCN.

Regarding venlafaxine (VNX), two TPs were found. The first with m/z 262.1802 and elemental composition $C_{16}H_{24}NO_2^+$ could be generated from further oxidation of metabolite ODV (m/z 264.1958). Second, TP yielded an accurate mass of 250.1802 ($C_{15}H_{24}NO_2^+$). VNF-TP1 and VNX-TP2 maximized at 15 min. Both TPs were identified as intermediate products of venlafaxine after the photocatalytic process by Konstas et al. (2019) [27].

Table 4. Retention time (R_t), elemental formula, mass error, and double-bond–ring-equivalent number (RDB) of parent compounds and transformation products (TPs) identified during the photocatalytic treatment by UHPLC-Orbitrap MS.

Parent Compounds/TPs	R_t (min)	Elemental Formula $[M + H]^+$	Δ (ppm)	RDB	Chemical Structure
Venlafaxine	3.60	$C_{17}H_{28}NO_2$	2.644	4.5	
VNX–TP1	3.47	$C_{16}H_{24}NO_2$	0.402	5.5	
VNX–TP2	3.30	$C_{15}H_{24}NO_2$	0.098	4.5	
O-desmethyl-venlafaxine	3.35	$C_{16}H_{26}NO_2$	3.011	4.5	
ODV-TP1	3.05	$C_{16}H_{24}NO$	1.629	5.5	
Quetiapine	3.75	$C_{21}H_{25}N_3O_2S$	1.391	10.5	
QTP-TP1	3.36	$C_7H_{15}O_2N_2$	1.598	1.5	
Fluoxetine	3.93	$C_{17}H_{19}NOF_3$	4.628	7.5	
FLX-TP1	3.50	$C_{10}H_{16}NO$	1.991	3.5	
FLX-TP2	3.75	$C_{10}H_{13}NO$	0.187	4.5	

According to previous published data, O-desmethyl venlafaxine is the main product of human metabolism at a rate of 90%, while N-desmethyl venlafaxine is also produced but only at a rate of 10%. Both TPs have been identified elsewhere during the photocatalytic process with O-desmethyl venlafaxine to represent the main TP, while degradation pathways were also discussed [28]. In our study, O-desmethyl venlafaxine with m/z 264.1954

($C_{16}H_{25}NO_2$) was identified. Only one TP of ODV was observed after 15 min with m/z 246.1852, corresponded to H_2O loss, yielded an elemental structure of $C_{16}H_{24}NO$, and was completely removed after 120 min of the photocatalytic process.

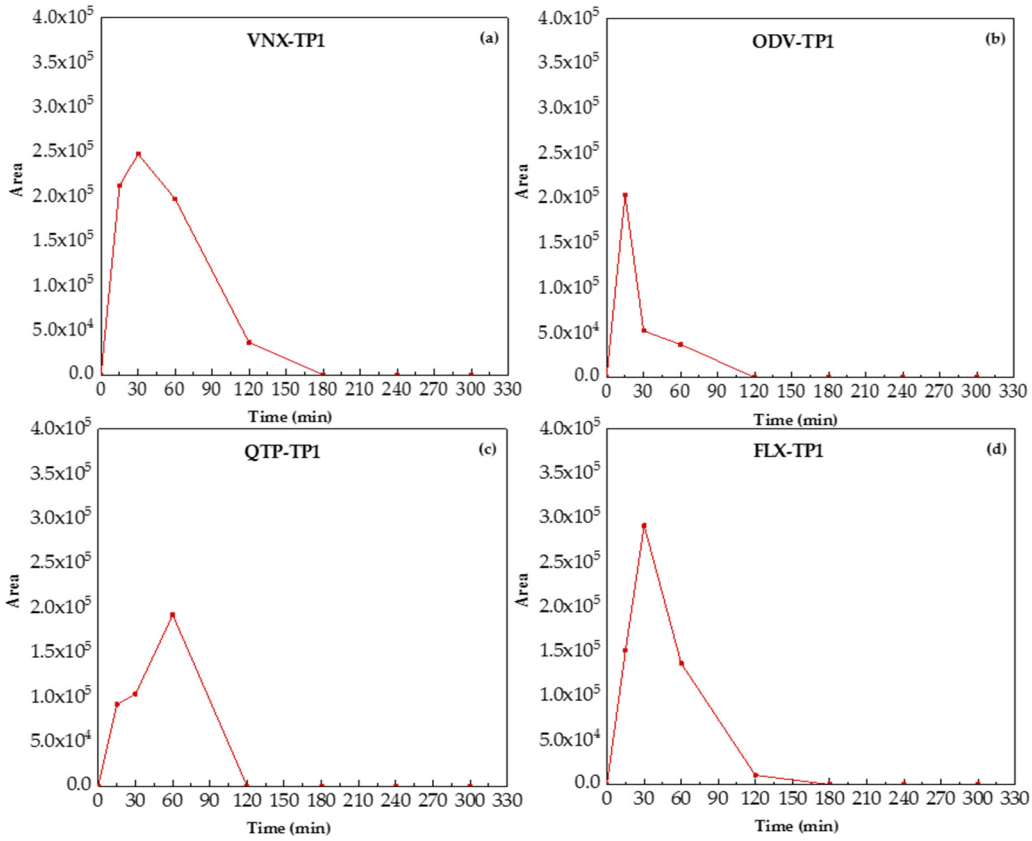


Figure 2. Evolution profiles of (**a**) venlafaxine TP1, (**b**) O-desmethyl venlafaxine TP1, (**c**) quetiapine TP1, and (**d**) fluoxetine TP1, formed by photocatalytic oxidation process at the laboratory-scale pilot plant using $1MoS_2/g\text{-}C_3N_4$.

Concerning quetiapine, one TP was observed. This TP exhibited an m/z of 159.1120 and peak up at 60 min. This TP has been reported by Skibinski as a TP formed after a photodegradation study of quetiapine [29].

As for fluoxetine, two TPs were identified. TP1 was m/z 166.1225 with the chemical formula $C_{10}H_{15}NO$. Moreira et al. (2020) also reported the finding of this TP in the photocatalytic degradation of Prozac by TiO_2 nanoparticles [30]. TP2 with molecular formula $C_{10}H_{13}NO$ provided a peak at m/z 164.1069, which indicates the loss of the trifluorotoluene and the oxidation of the alcohol produced in the corresponding ketone. Both TPs were observed after 15 min, maximized at 30 min, and completely degraded after 120 min.

Photocatalytic experiments in the presence of scavengers have been previously studied [19] for the degradation of phenolics using the same catalysts. Isopropanol (IPA), superoxide dismutase (SOD), and triethanolamine (TEOA) were used to scavenge $^{\bullet}OH$, $O_2^{\bullet-}$, and h^+, respectively. Based on the previous results, kinetics retardation follows the trend TEOA > SOD > IPA, suggesting mainly the participation of positive holes (h^+) and $O_2^{\bullet-}$ with $^{\bullet}OH$ being formed secondary in a minor extent. The critical role of holes in contaminant degradation using $g\text{-}C_3N_4$ catalysts was also elucidated previously [31]. Based on the above, the formation of the detected TPs or the absence of TPs related to $^{\bullet}OH$ attack such as hydroxyderivatives is consistent with the formation of major oxidant species.

3. Materials and Methods

3.1. Reagents and Chemicals

All reagents used in the experiments were of high purity grade (>97%). Bupropion hydrochloride (BUP) was obtained from LGC (Wesel, Germany). Amisulpride (AMS), amitriptyline (AMT), fluoxetine hydrochloride (FLX), and venlafaxine hydrochloride (VNX) were purchased from TCI (Zwijndrecht, Belgium). Carbamazepine (CBZ), citalopram (CIT), clozapine (CZP), O-desmethyl venlafaxine (ODV), and quetiapine (QTP) were purchased from Sigma-Aldrich (Darmstadt, Germany). Carbamazepine-d10 and fluoxetine-d5 hydrochloride were supplied from A2S (Saint Jean d'Illac, France). Individual stock solutions of each compound, as well as isotopically labeled internal standard solution, were prepared in methanol and stored at −20 °C. LC-MS-grade methanol, LC-MS-grade water, and Na_2EDTA grade were purchased from Fisher Scientific (Leicestershire, UK). Folin–Ciocalteu's phenol reagent and formic acid (purity, 98–100%) were obtained from Merck KGaA (Darmstadt, Germany). Sodium carbonate and *p*-hydroxy benzoic acid were supplied from Sigma Aldrich (St. Louis, MO, USA). Oasis HLB (200 mg, 6 cm^3) cartridges used for solid-phase extraction were bought from Waters Corporation (Milford, MA, USA).

3.2. Collection of Hospital Wastewater Treatment Plant Samples

Samples of real hospital wastewater treatment plant effluent were collected from the University hospital WWTP of Ioannina (Northwestern Greece) and used for all experiments. The hospital is an academic medical center that interrelates with Ioannina's University's School of Medicine and School of Nursing. It has a capacity of 800 beds and almost 45,000 people are treated in the hospitals' care clinics, while almost 130,000 people use the hospitals' casualty department every year. The HWWTP consists of a pretreatment step (grit-removal), flow equilibration tank, and a biological secondary treatment, with the final step being the disinfection with the addition of NaClO (15% solution). The hydraulic retention time (HRT) of the WWTP is 6 h, while the solid retention time (SRT) is 1.5 days. This plant discharges its effluent wastewater into the urban network, which results in the municipal WWTP; therefore, the assessment of its efficiency has substantial interest.

Secondary effluent, for all lab-scale experiments, was collected in jerrycans and transported immediately to the laboratory. Physicochemical parameters of the samples were determined by applying standard methods. The chemical oxygen demand (COD) was measured by a WTW Thermoreactor 3200 and a WTW pHotoFlex portable photometer by following the corresponding set test for each application (WTW, Weilheim, Germany). Five-day biochemical oxygen demand (BOD_5) was determined by means of a WTW OxiTop OC 110 system and a WTW TS 606-G/2-i thermostat cabinet (WTW, Weilheim, Germany).

3.3. Photocatalytic Materials

Two different semiconductor materials were used, i.e., graphitic carbon nitride (g-C_3N_4) (specific surface area: 35 m^2g^{-1}, particle size of 25 nm, E_g = 2.82 eV) prepared using urea as a precursor compound, and a composite catalyst 1%MoS_2/g-C_3N_4 (1MSCN) (specific surface area: 62.2 m^2g^{-1}, particle size of 9.5 nm, E_g = 2.66 eV). The synthesis and characterization of the semiconductor materials are described elsewhere [19]. The selection of 1MSCN material is based on our previous publication [19] that studied a series of composite g-C_3N_4/MoS_2 materials with different percentages (1, 2, 5, and 10%) of MoS_2 loadings, concluding that the catalyst with 1% MoS_2 loading was the most active toward the photocatalytic degradation of phenolics.

3.4. Photocatalytic Experiments

3.4.1. Solar Simulator

Photocatalytic experiments were carried out in a solar simulator apparatus Atlas Suntest XLS+ (Atlas, Germany) equipped with a xenon lamp (2.2 kW) and special filters in place to prevent the transmission of wavelengths below 290 nm. During the experiments, the irradiation intensity was maintained at 500 Wm^{-2}. In the wastewater photocatalytic

treatment process, aqueous solutions (250 mL) and the catalyst (100 mgL^{-1}) were transferred into a double-walled Pyrex glass reactor, thermostated by water flowing in the double-skin of the reactor. The suspension was spiked with a mixed standard solution of target psychiatric drugs at a concentration of 250 ngL^{-1}. To ensure the establishment of adsorption–desorption equilibrium onto the catalyst surface, the suspension was stirred by a magnetic stirrer in the dark for 30 min, before exposure to light. The wastewater samples were irradiated for 300 min. Samples were withdrawn at different time intervals and were centrifuged (Thermo Scientific, HERAUS Megafuge 8, Shanghai, China; 4400 rpm) for 20 min for the separation of the catalyst particles. The samples were filtered by 0.45 μm filters before extraction.

3.4.2. Laboratory-Scale Pilot Plant

Photocatalytic experiments were carried out also in a laboratory-scale pilot reactor (Ecosystem S.A., Barcelona, Spain) composed of a stainless-steel reactor of total volume 46 L equipped with ten UVA lamps (Philips PL-L 36W. UVA radiation 8.5W, UVA range 340–400 nm, λ_{peak} = 375 nm) and quartz filters. A polypropylene recirculation tank of a working volume between 55 L and 100 L was connected in series. Hence, the pilot plant behaved as a plug-flow reactor where water is circulating using a circulation pump. The experiment started with the addition of secondary effluent to the circulation tank spiked with a mixed standard solution of target psychiatric drugs at a concentration of 250 ngL^{-1} (amisulpride, venlafaxine, O-desmethyl venlafaxine, clozapine, citalopram, quetiapine, carbamazepine, bupropion, fluoxetine, and amitriptyline) following 15 min of homogenization by mechanical stirrer. Then, 100 mgL^{-1} of catalyst was added and for ensuring homogenization, the suspension was mechanically stirred in the dark for 15 min followed by recirculation for 30 min before exposure to light. The wastewater samples were irradiated for 360 min. Samples were withdrawn at different time intervals and were centrifuged for 20 min for the separation of the catalyst particles. The samples were filtered by 0.45 μm filters.

3.5. Extraction of Wastewater Samples

Concentration levels of psychiatric drugs in the raw and treated samples were determined using Ultra-High-Performance Liquid Chromatography-Orbitrap-Mass Spectrometry (UHPLC-Orbitrap-MS), after the Solid-Phase Extraction (SPE) procedure. The Oasis HLB (200 mg, 6 cm^3) cartridges were selected for the determination of the target analytes. After the filtration of the samples, the pH value was regulated to ~7. An appropriate volume of 5% Na_2EDTA solution was added (final concentration of 0.1% in the sample). The samples were spiked with the appropriate volume of internal standard mixture. The preconditioning of the cartridges was performed with 5 mL of LC-MC-grade methanol and 5 mL of LC-MS-grade water and then the samples were loaded into the cartridges and percolated with a flow rate of 6 mL/min. After the extraction, the cartridges were washed with 5 mL of LC-MS-grade water and dried for 20 min. Elution of the analytes was performed twice with 5 mL of LC-MS-grade methanol at 1 mL/min and the extracts were evaporated to dryness under a gentle stream of nitrogen by means of a Techne Dri-Block heater Model DB-3D. The final step was the reconstitution, which was performed with 500 μL of methanol: water 20:80 (v/v) with 0.1% formic acid, and the samples were stored at −20 °C until analysis.

3.6. LTQ-FT Orbitrap Instrument Operational Parameters

The analysis of the samples was performed by a UHPLC Accela LC system, connected with a hybrid LTQ-FT Orbitrap XL 2.5.5 SP1 mass spectrometer, equipped with an electrospray ionization source (ESI) (Thermo Fisher Scientific, Inc., GmbH, Bremen, Germany) as reported in our previous work. Identification and quantification of pharmaceuticals were acquired using full scan mode in positive and negative ionization. Collision-induced dissociation (CID) was performed for the data-dependent acquisition (full MS/dd-MS2)

and the mass tolerance window was set to 5 ppm. To process the data, Thermo Xcalibur 2.1 software (Thermo Electron, San Jose, CA, USA) was used. Chromatographic separation was performed on a reversed phase Hypersil Gold C18 (Thermo Fisher Scientific) analytical column (100 × 2.1 mm, 1.9 μm). In positive ionization (PI), two mobile phases, A: 0.1% formic acid in LC-MS-grade water, and B: 0.1% formic acid in LC-MS-grade methanol, were used. In negative ionization (NI), LC-MS-grade water and LC-MS-grade methanol were used as mobile phases A and B, respectively. The elution gradient in PI started at 95% A and remained for 1 min, progressed to 30% in 3 min, and then to 0% in 6 min and returned to 95% A after 3 min with re-equilibration of the column set at 1 min. The elution gradient in NI started with 90% A, remained for 0.5 min, progressed to 30% in 2 min, reached 10% in 3 min, decreased to 5% at 3.9 min, decreased to 0% at 4.5 min, and remained for 0.5 min. After 1 min, it returned to 90% A with re-equilibration of the column set at 2 min. The total run time for PI and NI was 10 and 8 min, respectively. In both cases, the injection volume was 20 μL and the flow rate was 0.4 mL/min. The oven temperature was maintained at 27 °C.

4. Conclusions

The results of the present study point out that heterogeneous photocatalysis using g-C_3N_4 catalysts is an effective treatment process for the elimination of psychiatric drugs from real hospital effluent wastewater samples. The photocatalytic pattern of the targeted compounds followed the pseudo-first-order kinetics. 1MoS_2/g-C_3N_4 presented higher photocatalytic performance than g-C_3N_4 in all experiments. All psychiatric drugs after the photocatalytic process were removed in percentages higher than 30% and 54% using g-C_3N_4 and 1MSCN, respectively. Five psychiatric compounds (amisulpride, venlafaxine, O-desmethyl venlafaxine, and quetiapine) were detected in inherent concentrations higher than LOQ, whereas fluoxetine was found in trace levels. Six transformation products were identified during the photocatalytic treatment; however, all of them were totally degraded at the end of the treatment.

Future studies should focus on the reuse of the catalyst and the monitoring of the toxicity along the treatment, as well as on the effective separation of the catalyst and its application on a larger pilot scale using natural solar irradiation.

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