Politechnika Śląska

Silesian University of Technology

UCZELNIA BADAWCZA

Extended Executive Summary

Degradation of selected drug used in COVID-19 therapy in the aquatic environment by means of solar light driven processes

By Humam Ahmed, M. Sc., M.Phil.

Supervisor: Prof. dr hab. inż. Ewa Felis

Doctoral Thesis in discipline "Environmental engineering, mining and energy"
Silesian University of Technology
Faculty of Energy and Environmental Engineering
Department of Environmental Biotechnology
Gliwice, Poland, 2025

1. Aim and Scope of the Work

Due to the COVID-19 outbreak, there has been an increase in the consumption of drugs used to treat the pandemic. As a result, these drugs are entering the aquatic environment either unchanged or only partially broken down. Even though the pandemic has subsided, scientists believe that the SARS-CoV-2 virus has become an endemic virus, meaning it will continue to affect the population periodically, like the flu virus. This indicates that society will need to adapt to living with the virus, and treatments for the infection will always be in demand, leading to continuous release of these drugs into the environment. ***Therefore, the aim of this work is to assess the extent to which these drugs degrade in the aquatic environment under the influence of sunlight and in photocatalytic degradation processes initiated by sunlight, as well as to determine the influence of the components of the aqueous matrix on the degradation process***.

The **specific objectives of the work** were:

i. To assess the susceptibility to degradation of selected drugs used in the treatment of COVID-19 in the broadly understood aquatic environment, using processes initiated by (artificial) sunlight.

ii. To determine the impact of selected aquatic matrix parameters on the efficiency of degradation of these drugs.

iii. Study the impact of real water matrices (e.g., salts, organic matter, inorganic anions) on degradation efficiency.

iv. Assessment of the selected photocatalysts "as tools" supporting the decomposition of selected drugs in the aquatic environment by means of solar-light driven photocatalysis.

v. Investigate the influence of operational parameters such as catalyst dose, pollutant concentration, and reaction time.

vi. Comparing the performance of various photocatalysts (e.g., TiO_2, ZnO, SnO_2, Ag-TiO_2 etc.).

vii. To evaluate the degradation kinetics of selected drugs under varying photocatalytic conditions (e.g., pH, light intensity, catalyst dosage). Compare the degradation efficiencies of single photocatalysts with combined ones such as SnO_2:ZnO).

viii. Study the degradation efficiency of different pharmaceutical drugs under controlled laboratory conditions.

ix. Model the degradation kinetics using common models like first-order, pseudo-second-order, or Langmuir adsorption kinetics and others.

The following **hypothesis** was tested:

H1. The degradation efficiency of COVID-19-related pharmaceutical compounds in aquatic environments can be significantly enhanced through solar-light-driven photocatalysis, with performance strongly influenced by photocatalyst type, water matrix composition, and operational parameters.

The findings of the above-mentioned research tasks allowed a comprehensive and realistic assessment of the environmental risk posed using drugs included in COVID-19 therapy, as well as the identification of environmental factors influencing the degradation of these drugs in aquatic environment. Also, COVID-19 drugs and their metabolites pose a specifically severe risk of water contamination in low-income countries because low-income countries depend on traditional wastewater treatment systems based on primary and secondary treatment techniques, with no advanced treatment options such as tertiary treatment. The selected approach to degrading COVID-19 drugs, photolysis and photocatalysis, occurs with sunlight (which should be understood as a combination of visible and UVA light) and the reactivity of a photocatalyst. The methodology was environmentally friendly, cost-effective, and is easily affordable for low-income countries.

2. Significance of the research work - State of the art/ Brief literature review

The properties of the SARS CoV-2 virus, causing the COVID-19 disease, made it global threat, triggering the outbreak of the pandemic in March 2020 and the effects of which are felt even after its expiry (Marc H. Bornstein, 2020). The vaccination campaign and the number of people who have naturally acquired immunity to the virus will undoubtedly

contribute to the slow extinction of the pandemic, however, many scientists believe that the SARS CoV-2 virus has such features that it will remain endemic, i.e., it will be constantly present in the environment (such as the influenza virus) (Ahmed & Felis, 2023).The effectiveness of COVID-19 drugs and virus contamination in wastewater depends on water quality, and environmental factors affect virus vulnerability and inactivation (Nannou et al., 2020). It is important to consider the impact of antiviral drugs on the environment, as seasonality alters antiviral fate and transit in the aquatic environment.

Micropollutants contaminate the natural environment and end up in key aquatic systems. WWTPs are often identified as the primary point source, but there is concern that prolonged exposure to pharmaceuticals could lead to serious health issues (Al Aukidy et al., 2012). Antivirals often excrete mostly in their parent dose's bioactive state, and the human body's metabolism of antivirals has a considerable impact on how much of them are discharged into the environment. The surface waters are the initial recipient of the treated wastewater containing these substances, acting as a barrier between the other environmental compartments (Jain et al., 2013). The aquatic environment contains a diverse spectrum of natural biotic and abiotic activities that can be responsible for the attenuation of these compounds through transformation to other substances or accumulation in different phases. Biodegradation, photodegradation, sorption, oxidation, and other abiotic mechanisms regulate the survival of pharmaceutical chemicals in the aquatic environment (Heberer, 2002).

To remove the pharmaceutical pollutant, several methods have been employed such as adsorption, filtration, coagulation, ion exchange, and biological treatments. These methods have some pros and cons. Among them, photocatalysis stands out as an effective technique, particularly when activated by sunlight, which reduces the overall cost of treatment. Therefore, ***this work determined the efficiency of photochemical decomposition of drugs and kinetic constants depending on matrix composition, radiation intensity, dose, and photocatalyst type and contributed to better understanding of abiotic degradation in the aquatic environment. Furthermore, this was the first study to explored photocatalytic degradation of anti-viral drug isoprinosine with a focus on degradation kinetics, and real-world applicability. In addition, the study on ritonavir and the evaluation of the percentage removal of remdesivir using a two-phase kinetic model based on a unique adsorption–desorption dynamic represented a novel contribution to this field. To the best of our***

knowledge, no previous studies have reported such an approach in the available literature. This study also developed an eco-friendly and energy-efficient approach to tackle pharmaceutical pollution.

3. Materials and Methods

3.1 Chemical used

Pure analytical standards of isoprinosine (IPN), ritonavir (RTR), and remdesivir (REM), (Cayman Chemicals, Poland); acetic acid and sodium acetate for an acetate buffer (pH 5.0); 99% formic acid; analytical grade acetonitrile (ACN); and methanol (POCH S.A., Poland). Additionally, 99.9% pure TiO_2 P25 supplied by (Degussa Germany), ZnO, SnO_2, ZrO_2, and $BaWO_4$ were utilized as commercial photocatalyst, along with the ionic compounds NaCl, Na_2SO_4, $CaCO_3$, and $NaNO_3$ were used as a source of anions, all of them were purchased from Sigma-Aldrich. $AgTiO_2$ and $BaTiO_3$ were synthesized in the laboratory and used as photocatalysts in this study. Finally, a 12% v/v solution of H_2O_2 was obtained from Avantor, Poland.

3.2 Experimental Methodology

3.2.1 Chromatographic Method Development

Chromatographic analyses were performed using an HPLC–UV system (Thermo Scientific Dionex UltiMate 3000). The analytical conditions were optimized through the determination of absorption maxima, selection of the stationary phase, and adjustment of the mobile phase composition. Particular attention was given to the choice of column type (e.g., C18, C8), mobile phase components, pH, and column temperature. Method validation procedures included the assessment of linearity, precision, accuracy, limit of detection (LOD), limit of quantification (LOQ), and the preparation of calibration curves for the selected pharmaceutical compounds.

3.2.2. Sunlight-Induced Abiotic Degradation Experiments

Abiotic photodegradation studies were conducted using a Solar Box 1500e photoreactor (CO.FO.ME.GRA, Italy), equipped with an air-cooled xenon lamp capable of simulating natural solar irradiation. Experiments were performed under a controlled irradiance of 500 W/m^2. Depending on the stage of the investigation, degradation tests were carried out in aqueous solutions of the target pharmaceuticals; isoprinosine (IPN), ritonavir (RTR), and

remdesivir (REM), either as pure drug solutions or in the presence of selected inorganic anions (SO_4^{2-}, NO_3^-, HCO_3^-, CO_3^{2-}, Cl^-) in three different water matrices i.e., Milli-Q water (MQW), tap water (TW), and surface water (SW). Exposure time, solution volume, and other operational conditions is included in detailed in full dissertation.

3.2.3. Photocatalytic Degradation of selected pharmaceutical

The susceptibility of selected anti-COVID-19 pharmaceuticals (IPN, RTR, and REM) to sunlight-driven degradation was additionally evaluated in real surface water matrices. In contrast to abiotic tests, no inorganic anions were added. Instead, different doses of selected catalysts TiO_2 P25, ZnO, ZrO_2, $BaWO_4$, Ag-TiO_2, $BaTiO_3$, and SnO_2 were applied to assess their impact on degradation efficiency. Among the photocatalysts used, Ag-TiO_2 and $BaTiO_3$ were synthesized by fellow researchers as part of separate projects; therefore, their capabilities to degrade the selected drugs.

In the case of photodegradation assisted with H_2O_2, the studies were carried out with a selected concentration of H_2O_2; 125 µL (108.8 mg/L), 250 µL (217.5 mg/L), and 500 µL (435 mg/L) and with a specific dose 2.0 mg/200 mL of each drug (IPN, RTR, REM).

3.2.4. Analytical Control of Degradation Processes

Throughout all degradation experiments, pharmaceutical concentrations were monitored using the HPLC methods optimized in the chromatographic development stage. Complementary measurements included UV/Vis absorbance spectra of samples before and after exposure (Merck UV/Vis spectrophotometer, Germany).

Total organic carbon parameters such as non-purgeable organic carbon (NPOC) and total organic carbon (TOC) were quantified using a Shimadzu TOC-VCSH analyzer. Concentrations of inorganic anions present during the experiments were determined using a Dionex Aquion ion chromatograph (A.G.A. Analytical, Poland).

3.2.5. Kinetic and Statistical Analysis

Statistical evaluation and data processing were performed using Microsoft Excel and Origin Pro software. Reaction kinetics were assessed by fitting experimental data to pseudo first order, pseudo second order and two-phase adsorption-desorption kinetic models. Kinetic

parameters were calculated to identify the reaction mechanism and to evaluate the rates of reactant degradation and product formation.

4. Results and Discussion - selected cases

4.1 Photolysis Experiments

Photolysis experiments under simulated solar irradiation (500 W/m^2) showed that IPN was highly photostable, with only 9% degradation in Milli-Q water after 60 minutes and 8–14% removal in tap and surface waters after 120 minutes. Among them the highest pseudo drug degradation rate was observed in MQW i.e., kt = 0.0007 min^{-1}. In case of RTR, it degraded moderately, reaching 15% removal in Milli-Q water (kt = 0.0012 min^{-1}), 38% in tap water (kt = 0.0005 min^{-1}), and 51% in surface water (kt = 0.001 min^{-1}) after 120 minutes. REM showed limited but noticeable degradation, with removals of 15% in Milli-Q water (kt = 0.0016 min^{-1}), 27% in tap water (kt = 0.0005 min^{-1}), and 23% in surface water (kt = 0.0004 min^{-1}). In all cases, the degradation followed pseudo-first-order kinetics summarized in Table 1. These results indicated that IPN may not go further changes under the environmental conditions.

Table.1. Kinetic parameters–first-order pseudo constants of photolysis of selected drugs

Drugs	Water matrices	[a]*Kt*, min^{-1}	[b]½ t , min^{-1}	[c]R^2
Isoprinosine	MQW	0.0007	990.2	0.6092
	TW	0.0003	2310.5	0.8154
	SW	0.0001	6931.5	0.8726
Ritonavir	MQW	0.0012	577.6	0.8201
	TW	0.0005	1386.3	0.8488
	SW	0.001	693.1	0.9583
Remdesivir	MQW	0.0016	433.2	0.8563
	TW	0.0005	1386.3	0.9488
	SW	0.0004	1732.9	0.9124

a). Pseudo first order kinetic rate constant, b). Half-life of the reaction, c). Coefficient of determination.

4.2 Photocatalytic Experiments

4.2.1. Isoprinosine

Photocatalytic experiments of IPN (2.0 mg/L) under stimulated solar irradiation (500 W/m^2) was performed using seven different selected photocatalysts. Among them three photocatalysts (TiO_2 P25, ZnO, SnO_2) only in MQW results were chosen to be mentioned in this executive summary of the thesis. Results revealed that at a dose of 5.0 mg/L of TiO_2 P25 and ZnO, IPN was degraded significantly: TiO_2 P25 achieved a complete degradation of 100%, while ZnO reached 88% after reaction times of 30 minutes and 120 minutes, respectively, as shown in Figure 1a. Furthermore, TiO_2 P25 and SnO_2, at a dose of 10.0 mg/L, achieved degradation rates of IPN 100% and 10% after 30 minutes and 90 minutes, respectively in MQW (Figure 1b). In case of TW , at photocatalyst dose of 10.0 mg/L IPN degraded by 36% with ZnO, and by 15% with both TiO_2 P25 and SnO_2. While in SW, TiO_2 P25 was able to degrade IPN by 23%, while ZnO achieved a degradation rate of 22% (Figure 1c). In all cases, the degradation followed pseudo-first-order kinetics.

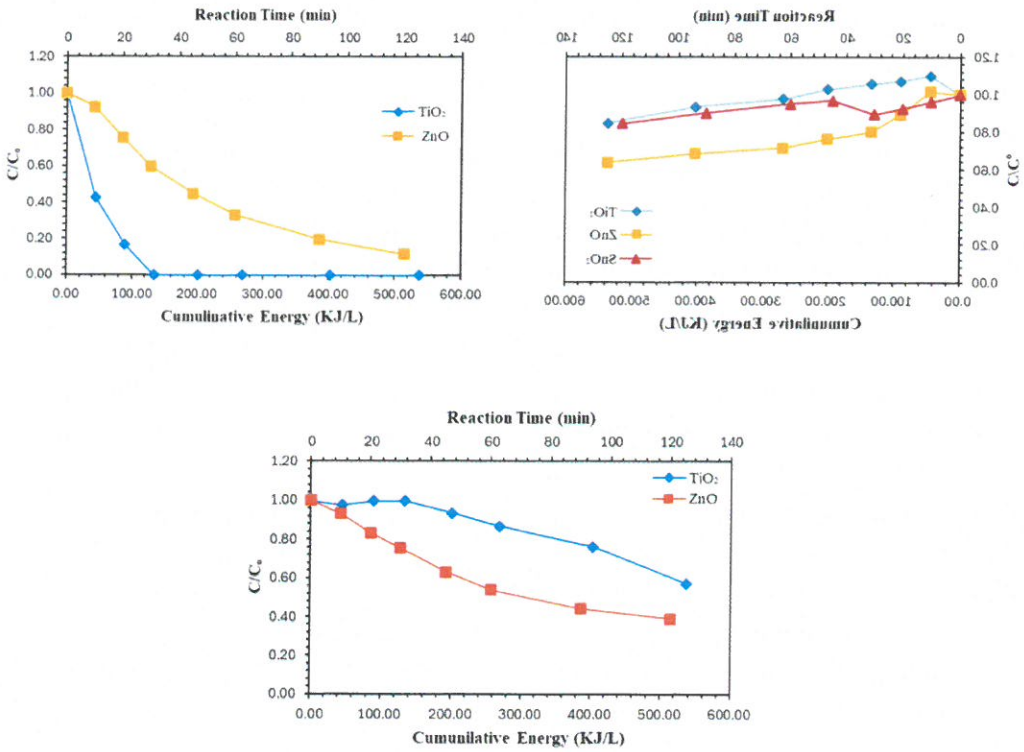

Figure. 1. Degradation of anti- COVID drug IPN in a). MQ-water, b). TW, c). SW by selected photocatalysts

4.2.2. Ritonavir

The photocatalytic activity of selected photocatalysts at a fixed dose of 10.0 mg/L was evaluated using the anti-COVID drug RTR, a class of protease inhibitor, in three different water matrices (MQW, TW, and SW) under UV light (500 W/m^2). The results indicated that RTR was completely adsorbed (100%) on the surfaces of ZnO and SnO_2:ZnO (2:1) within just 30 seconds of the reaction in all three water matrices. Among the selected photocatalysts, TiO_2 P25 showed 72% adsorption on its surface after 120 minutes of the experiment. It was also observed that the initial concentration of RTR (2.0 mg/L) remained stable for the first 45 minutes; however, it decreased rapidly afterward, with the equilibrium point reached 60 minutes into the reaction. The kinetic parameters followed the Langmuir adsorption isotherm mentioned in Table 2.

Table.2. Kinetic parameters–Langmuir Isotherm model for ritonavir adsorption

Process	Water matrices	Conc., mg/L	[a]*Kt*, min^{-1}	[b]R^2	[c]KL L/mg	[d]q_{max} (mg/g)
UV-TiO_2 P25	MQW	10.0	0.2661	0.9995	1330.5	3.76
	TW		0.0286	0.9927	5720	34.97
	SW		0.0256	0.9995	5120	39.06
UV- ZnO	MQW	10.0	0.2532	0.9992	5064.0	3.95
	TW		0.0265	0.9954	8833.3	37.74
	SW		0.0532	0.9958	2660.0	18.80
UV- SnO_2:ZnO	MQW	10.0	0.2605	0.9657	13025.0	3.84

a). Pseudo first order kinetic rate constant, b). Coefficient of determination, c). Langmuir constant, d). Maximum adsorption capacity.

4.2.3. Remdesivir

The adsorption behavior of the REM (1.0 mg/L) on two widely used photocatalysts; TiO_2 P25 and ZnO (20.0 mg/L) was investigated through both experimental measurements and theoretical modeling in selected aquatic matrices (MQW, TW, and SW). Both TiO_2 P25 and ZnO exhibited strong adsorption tendencies, with the experimental data showing high surface coverage values over time. In the case of TiO_2 P25, adsorption reached approximately 98.92% by 120 minutes, while ZnO achieved a comparable value of 81% within the same duration.

This suggests that, despite having different physicochemical properties, both materials are effective in retaining the target compound on their surfaces under the given experimental conditions. Table 3 provides the information on kinetic parameters of two-phase adsorption desorption model for REM under light conditions.

Table.3. Kinetic parameters–Two-phase adsorption desorption model for remdesivir under light conditions

Process	Water matrices	*Kads.*	*Kdes*, min^{-1}	*Kt*, min^{-1}	θ_{max} Model	θ_{max} Exp.	$^{a}\theta_{eq}$	R^2
UV-TiO_2 P25	MQW	0.0251	0.0002	0.0253	0.94	1.00	0.99	0.8610
	TW	0.0250	0.001	0.0251	1.00	0.82	1.00	0.8553
	SW	0.0118	0.0000	0.0118	0.74	0.99	1.00	0.9655
UV- ZnO	MQW	0.0236	0.0000	0.0236	0.94	0.81	1.00	0.8747
	TW	0.2500	0.0050	0.2550	0.98	0.83	0.98	0.8226
	SW	0.0100	0.0001	0.0010	0.67	0,99	0.91	0.9655

a). Surface coverage at equilibrium

4.3 Photolysis assisted with H_2O_2

To assess the degradation susceptibility of the drugs used in this study, varying concentrations of H_2O_2, i.e., 125 µL (108.8 mg/L), 250 µL (217.5 mg/L), and 500 µL (435 mg/L) were utilized in the presence of solar light (500 W/m^2) in Milli-Q water (MQW), chosen for its high purity. results of the degradation of the antiviral drug IPN under UV-assisted conditions with H_2O_2 at the concentrations mentioned above. The findings indicate that IPN is completely degraded (100%) with 125 µL and 250 µL of H_2O_2 after 30 minutes of reaction time (Figure 3a). In contrast, with 500 µL of H_2O_2, IPN achieved complete degradation within 120 minutes. For the second drug, RTR, complete degradation (100%) was achieved within 45 minutes across all tested concentrations of H_2O_2 (Figure 3b). In the case of REM, the first FDA-approved drug used to treat COVID-19, degradation rates were 55% for 125 µL, 53% for 250 µL, and 83% for 500 µL of H_2O_2 after 120 minutes of the process (Figure 3c).

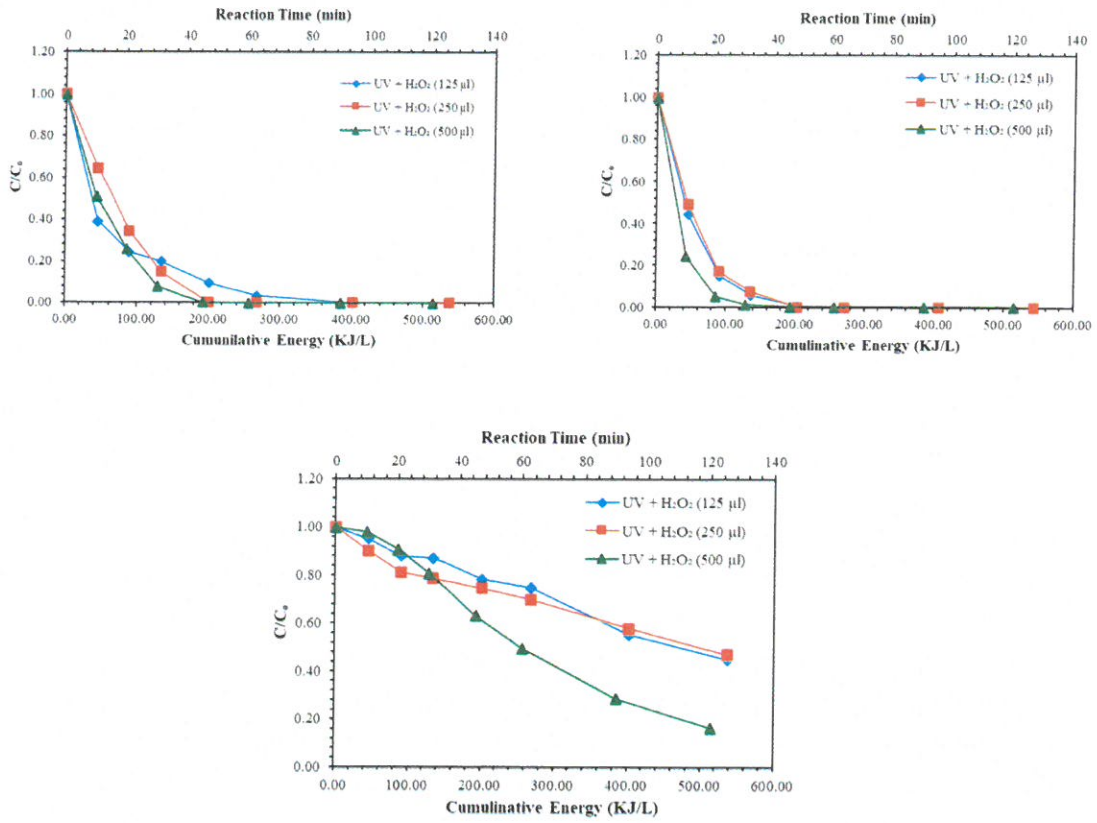

Figure. 3. UV - assisted H_2O_2 degradation of a). IPN, and b). RTR c). REM at different concentration of H_2O_2 in MQ water

4.4 Sorption Tests

Dark-condition experiments provided a baseline for distinguishing physical adsorption from true photodegradation, which is essential when assessing the performance of semiconductor-based treatment systems. For IPN, the highest adsorption-driven removal was observed with TiO_2 P25 (33%) and ZnO (26%) after 90 minutes. RTR exhibited particularly strong adsorption, occurring within the first 30 seconds, reflected by high Langmuir constants of 12,515 mg/L (TiO_2 P25), 823.33 mg/L (ZnO), and 555,432.1 mg/L (SnO_2:ZnO). The consistently high KL and q_{max} values confirmed strong affinity of RTR for the catalyst surfaces, and all adsorption data followed the Langmuir isotherm model.

For REM, adsorption/desorption behaviour on TiO_2 P25 and ZnO was well described using a two-parameter equilibrium model, with strong agreement between experimental and predicted surface coverage (R^2 = 0.9624 and 0.9197, respectively). Since these tests were performed in the absence of light where photocatalytic pathways are inactive and the observed

decreases in concentration are attributed solely to adsorption onto the semiconductor surfaces rather than chemical transformation.

4.5 Experiments in the presence of selected anion as a matrix component

The susceptibility to photodegradation of antiviral drug, isoprinosine (IPN), at ambient conditions in MQW and TW was studied in the presence of selected inorganic anions (SO_4^{-2}, Cl^-, NO_3^-, and CO_3^{-2}), as the main components of inorganic environmental matrices. The study was performed with 2.0 mg/L concentration of IPN at solar light irradiance (500 W/m^2), and photocatalysts like: TiO_2 P25, ZnO, and SnO_2. IPN was quantified by HPLC method at the wavelength of 260 nm. The photocatalysis of IPN is well described by pseudo-first-order kinetics. The highest value of the pseudo-primary rate of degradation constant for the IPN recorded for photocatalysis with 20.0 mg/L of pure TiO_2 P25 in the presence of NO_3^- ion (50.0 mg/L) and was 0.0334 min^{-1} with the correlation coefficient (R^2) value of 0.8875 in MQW. In the case of tap water, in the presence of SO_4^{-2} ions (250.0 mg/L), the highest pseudo-primary rate of degradation constant for the IPN was recorded by pure TiO_2 P25 i.e., 0.0481 min^{-1} with R^2 value of 0.9862. Results confirmed that IPN is degraded by pure TiO_2 P25 (100% after 30 and 90 min) in the presence of CO_3^{-2} in milli-Q and tap water, respectively. Results also show that in MQW, SnO_2 was able to degrade IPN completely (100%) after 90 min of the reaction time in the presence of NO_3^- ions only. It was found that in MQW, IPN was only slightly (up to 25%, 21%, and 29% after 2 hours) degradable by SnO_2, in the presence of chloride, carbonate, and sulfate ions respectively, which may be due to the several reasons such as its broad bandgap of 3.6 eV limits the absorption of UV light, leading to limited solar light utilization and due to the significant recombination of photo generated electrons and holes.

4.6 Mineralization

The study also examined the mineralization susceptibility of the tested drugs, i.e., IPN, RTR, and REM, in MQW, TW, and SW matrices for 120 minutes. Strong matrix effects were observed. IPN demonstrated effective mineralization only in MQW, with a significant decrease in TC, NPOC, and TN values relative to the initial concentration, whereas in tap water it showed minimal changes between the initial concentration and the concentration after the irradiation process. RTR remained largely stable in all matrices. REM exhibited the highest photodegradation, with a 50–65% decrease in TOC in all water types, indicating

relatively effective mineralization despite the complex background, particularly in surface water.

Overall, the mineralization efficiency of the tested drugs was highest in ultrapure water (MQW) and significantly lower in tap water (TW) and surface water (SW). These results indicate that natural sunlight alone is not sufficient to completely remove these antivirals from real environmental waters, especially those rich in organic matter or inorganic components.

5. Conclusion

This research successfully achieved its primary objective of investigating the photodegradation behavior of selected COVID-19 pharmaceutical compounds in aquatic environments under simulated solar irradiation. The results demonstrated that direct photolysis alone was not fully satisfactory for effective degradation due to the inherent photostability of the studied drugs i.e., IPN, RTR, and REM and the influence of water matrix composition. However, the incorporation of selected photocatalysts, and in particular, such as TiO_2 P25, and SnO_2 and their composites particularly the TiO_2 and ZnO significantly enhanced degradation efficiency at the catalytic dose 20 mg/L, confirming the potential of solar-driven photocatalysis as a viable treatment approach. The effects of key operational parameters, including catalyst dosage, pollutant concentration, and reaction time, were systematically evaluated, providing insights into the optimal conditions for maximum degradation performance. Kinetic modeling further revealed that the degradation followed pseudo-first-order behavior, supporting the reproducibility and predictability of the process. ***Overall, the findings confirm the research hypothesis and contribute valuable knowledge toward developing sustainable, solar-assisted advanced oxidation processes for the removal of antiviral and other pharmaceutical pollutants from aquatic environments.***

1. The results confirm that simple solar photolysis is not an effective degradation pathway for selected antiviral drugs due to their low light absorptivity and matrix interferences. However, solar-driven photocatalysis proved to be a promising, sustainable method for their removal, particularly using composite catalysts such as SnO_2:ZnO. These findings contribute valuable data to the limited body of knowledge on antiviral degradation and support the development of solar-based advanced oxidation processes for water treatment. In case of IPN, the highest pseudo drug degradation rate during photolysis was observed in MQW (kt = 0.0007 min^{-1}) with R^2

value of 0.6092. Similarly, in RTR and REM the highest pseudo drug degradation rate was also noted in MQW i.e., kt = 0.0012 min^{-1} (R^2 = 0.8201) and kt = 0.0016 min^{-1} (R^2 = 0.8563) , respectively.

2. Isoprinosine (IPN) underwent significant degradation under AOP conditions, with kinetic analysis best described by a pseudo-first-order model. This indicates a dominant reaction pathway governed by hydroxyl radicals or other short-lived reactive intermediates, especially under photocatalytic conditions. The addition of H_2O_2 enhanced the photolytic degradation rate, suggesting synergistic effects in reactive oxygen species generation. It has been observed that under UV-H_2O_2 experiments, the highest drug degradation rate was achieved with the 500 µL (435 mg/L) i.e., kt = 0.0302 min^{-1} (R^2 = 0.9473). IPN also shows the degradation w.r.t time using different selected photocatalysts in all three aquatic matrices. Among selected photocatalysts, IPN showed strong degradation in the presence of UV-TiO_2 P25 (10.0 mg/L) with kt = 0.0105 min^{-1}, correlation coefficient value of R^2 = 0.9159 in MQW. While in TW and SW, the highest drug degradation rate was observed with 20 mg/L ZnO i.e., kt = 0.0101 min^{-1} and kt = 0.0053 min^{-1} respectively.

3. In contrast, ritonavir (RTR) exhibited strong adsorption onto the surface of selected photocatalysts for example, TiO_2 P25 (kt = 0.0286 min^{-1} ; KL= 5720 L/mg), ZnO (kt = 0.2532 min^{-1}; KL= 5064 L/mg), and SnO_2:ZnO (1:2) (kt = 0.2605 min^{-1}; KL= 13025 L/mg) in MQW, which limited its photocatalytic degradation. The equilibrium data aligned well with the Langmuir isotherm, indicating monolayer adsorption on a homogenous surface. This suggests that while photocatalysis may not be effective for degrading RTR, its removal through adsorption could still be harnessed, particularly in systems designed for recovery or reuse of the adsorbent.

4. Remdesivir (REM) displayed a unique adsorption–desorption dynamic. It rapidly adsorbed onto the photocatalyst surface, followed by a gradual desorption phase. This reversible behavior was best described by a two-phase model, reflecting both rapid surface interaction and subsequent release back into solution. This phenomenon highlights the complexity of photocatalyst-drug interactions, which can be influenced by physicochemical properties of both the compound and the photocatalyst, in three different matrices.

Furthermore, the study explored the influence of inorganic ions i.e., (SO_4^-, Cl^-, NO_3^-, and CO_3^-) commonly found in natural waters were selected for the study with IPN and RTR only. These ions showed varied effects on degradation efficiency, either scavenging reactive species or altering surface charge interactions, further reinforcing the importance of matrix composition in environmental applications of AOPs. Overall, the findings emphasize the need for tailored AOP strategies depending on the physicochemical nature of the target contaminant. A thorough understanding of reaction kinetics, adsorption behaviour, and environmental influences is essential for optimizing degradation pathways and improving the sustainability of water treatment technologies.

6. References

Ahmed, H., & Felis, E. (2023). Drugs used in COVID-19 therapy and their effects on the environment. *DESALINATION AND WATER TREATMENT*, *301*, 52–62. https://doi.org/10.5004/dwt.2023.29574

AlAukidy, M., Verlicchi, P., Jelic, A., Petrovic, M., & Barcelò, D. (2012). Monitoring release of pharmaceutical compounds: Occurrence and environmental risk assessment of two WWTP effluents and their receiving bodies in the Po Valley, Italy. *Science of the Total Environment*, *438*, 15–25. https://doi.org/10.1016/J.SCITOTENV.2012.08.061

Heberer, T. (2002). Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: a review of recent research data. *Toxicology Letters*, *131*(1–2), 5–17. https://doi.org/10.1016/S0378-4274(02)00041-3

Jain, S., Kumar, P., Vyas, R. K., & Dalai, A. K. (n.d.). *Occurrence and Removal of Antiviral Drugs in Environment: A Review*. https://doi.org/10.1007/s11270-012-1410-3

Marc H. Bornstein. (2020). *Psychological Insights for Understanding COVID-19 and Families, Parents, and Children* (1st ed., Vol. 1). Routledge.

Nannou, C., Ofrydopoulou, A., Evgenidou, E., Heath, D., Heath, E., & Lambropoulou, D. (2020). Antiviral drugs in aquatic environment and wastewater treatment plants: A review on occurrence, fate, removal and ecotoxicity. *Science of the Total Environment*, *699*. https://doi.org/10.1016/J.SCITOTENV.2019.134322