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Laundry wastewater treatment under detergent-free environment and reaction kinetic analysis of ozonation technique for the recycling and other applications

Siyam Khalid[a], Abdul Wahab[a], Abdullah Yasar[a,*], Rameesha Tanveer[a], Amtul Bari Tabinda[a], Muhammad Zakaullah[b]

[a]*Sustainable Development Study Centre, Government College University, Lahore 54000, Pakistan, email: yasar.abdullah@gcu.edu.pk*
[b]*Centre for Advanced Studies in Physics, Government College University, Lahore 54000, Pakistan*

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ABSTRACT

The current study aims to find an effective strategy for performing the laundry process, which conserves water and eliminates detergents. The experimental design was done on a fabric sample contaminated with soil, color, and blood stains in a washing machine connected to an ozone generator. After treatment, its effectiveness in removing stains and sterilizing cloth against a certain type of bacteria was checked and compared with common detergent used in household laundry. The ozonation process was used for the decolorization of tea, ketchup, soil, and ink samples, which further removed tea, and ketchup stains within 30 min wash time, and soil stains in 60 min wash cycle. The removal efficiency of color with ozonation was achieved by about 90%. In the sterilization phase, ozone killed 98% of germs in 15 min wash cycle. Its efficiency was 9 times higher compared to the common detergent used in laundry. The characterization of physico-chemical parameters such as pH, temperature, and electrical conductivity remained constant. The wastewater of ozonated laundry had lower biological oxygen demand, and chemical oxygen demand. Ozone laundry for a single medium-size family saves almost 1 lac L of water annually. Moreover, it saves 15,000 Rs (USD 73.17) on a detergent cost for a single medium-size family per annum. This technique has been considered cost-effective, the operational cost of an ozone generator for a year was 1,412 Rs (USD 6.89). This ozonation technique in laundry has enhanced the wash process, increased fabrics' shelf-life, eliminated detergents, and chemical consumption, and reduced the number of rinses. Hence, the ozone treatment proved to be the most feasible and viable option for recycling, cleaning, and sterilizing clothes in hospitals, and domestic and industrial laundry.

Keywords: Laundry wastewater; Advanced oxidation processes (AOPs); Ozonation; Detergent-free environment

1. Introduction

Over the last previous years, domestic wastewater treatment has gathered considerable attention in developing countries. A substantial portion of domestic wastewater consists of laundry effluents. A typical laundry machine generates 50–200 L of effluent per wash [1,2]. The average discharge of laundry wastewater is approximately 190–2,106 L/d, which is generated by institutional, domestic, and industrial arenas [3,4]. This resultantly indicates a potent renewable resource for reuse purposes in all sectors, including metropolitan, agriculture, domestic, and institutional areas [5]. The organic constituent found in laundry wastewater includes soaps, detergent, aromatic solvent, oil, fats, grease, and biological substance. The inorganic substances include heavy metals, soil, dust, sand, metal ion, and particles. These substances increase the chemical oxygen demand (COD), biological oxygen demand, and total suspended

* Corresponding author.

solid of laundry wastewater [6]. The contributing factor to water pollution from laundry effluent is detergents. The laundry wastewater is based on the concentration, type, and number of various chemicals, soil removed during the washing process, and the garments' type to be cleaned [7].

The laundry wastewater has high organic content (1,200–25,000 mg/L) measured by COD and also contains higher values of surfactants, total suspended solids, nutrients, pH, pathogens, salts, and phosphates [8]. Detergents are mostly comprised of surfactants such as linear alkyl benzene sulfonates, sulfonates, olein sulfonate, sulfates, buffers like sodium tripolyphosphate, and other long carbon compounds [9]. Surfactants above 0.5 mg/L in water are harmful to health and make water treatment essential [10]. These surfactants are not completely degraded in the laundry process. This can only be degraded by certain microorganisms. Their release through laundry wastewater leads to the development of massive foam in streams and rivers. Phosphate is another significant component of detergents. It enters the water through laundry wastewater and causes eutrophication, resultantly in nutrient enrichment. The blooms reduce oxygen penetration in water, caused by defective absorption of dissolved oxygen in the water [11].

The most extensively studied and feasible methods for the treatment of laundry surfactants are biological treatment methods [11,12]. Changes in water chemistry and laundry types have made surfactant recalcitrant and non-biodegradable which has increased activity and toxicity [12]. In the past few decades, the treatment of these surfactants has gathered considerable attention. Different treatment methods have been introduced for the treatment of ionic surfactants such as ion exchange, wet air oxidation, membrane filtration, coagulation and filtration, photocatalytic degradation, Fenton, ozonation, and other advanced oxidative processes [13]. The possibility of complete mineralization and zero sludge makes the advanced oxidization process an attractive approach. The advanced oxidation process involves ozonation [9,14,15], direct UV [16], H_2O_2 [17], TiO_2 [18], persulfate, photocatalysis [19], and Fenton [9,19,20]. These processes can be used individually or combined to produce strong oxidizing OH^- radicals in the solution. The hydroxyl radicals have a high oxidative potential of about 2.80 V. Previous studies on ozonation in wastewater have shown that it reduces 25%–60% COD in laundry wastewater [21]. Furthermore, ozone is used for surfactant removal in laundry wastewater. It eliminates detergent use and pollution caused by detergent surfactants.

In ozone-based laundry, O_3 reduces costs such as water, energy, and chemicals [22]. The ozonation process has the potential to treat laundry wastewater without generating any sort of secondary waste materials and is 13 times more dissolving power compared to oxygen [23]. Ozone reduces wash time by 20%, chemicals by 45%, and water consumption by 90%. Ozone also destroys faecal material and body fluids and order, therefore, it reduces or eliminates the need for detergent or fragrant in laundry applications [24]. To perform typical laundry water is warmed because of the high temperature of the chemical reaction between water and detergent. In alkaline conditions (laundry wastewater), the higher oxidative potential has the ability to increase the treatment efficiency. Ozone due to its high reactivity works best at below 25 temperature reduces which reduces up to 40%–60% of energy consumption. The other benefit of ozone laundry includes softer clothes and clean smelling [25]. Ozone keeps water pH normal, which eliminates the need for additional agents which are added in industrial laundries to balance water pH. Laundering processes are a series of steps that uses large amounts of water at every step. Ozone reduces these washing steps which contributes to a large amount of water saving [25].

By incorporating the scientific gaps, the current study focuses on providing a detergent-free environment by treating laundry wastewater with an ozonation process. This is valuable for the reduction in water usage, and water and soil pollution in the laundry process. In this study, cleanness and complete removal of microorganisms were achieved in laundry clothes. Moreover, energy consumption for the ozonation process was also measured to optimize the treatment's cost-effectiveness. In addition, analysis of reaction kinetics was also evaluated to understand the reaction mechanism.

2. Materials and methods

2.1. Experimental design

2.1.1. Ozone generator and washing machine configuration

The ozonation treatment was conducted through a Plexiglass ozone reactor (2.5 cm diameter) to treat the laundry wastewater. The ozone generator's flow rate (OZ-10G: dimensions 350 mm × 250 mm × 600 mm) was 350 mg·O_3/h at 25°C. To calibrate the ozone reactor, ozone was produced in the form of bubbles in the deionized water for 10 min to maintain the ozone dose prior to initiating the treatment. An ozone dose of approximately 10 g·O_3/h was used. The ozone reactor was attached to the washing machine. A small-sized domestic washing machine was used having a 45 L water capacity. The tube was designed artificially inside the machine in which the ozone tube is placed. A lid was used to cover the machine to increase the residual time. At the end of the ozone tube, gray porous rock was placed, through which the ozone bubbles were generated. Fine bubbles were formulated and oxygen was completely dissolved in order to put clothes in the washing machine.

2.1.2. Stain removal test

The 3 pieces of 1 m × 1 m cloth size were used and stains of samples such as tea, ketchup, and soil were placed on separate cloths. The 15 L were put into the washing machine. The ozone tube was placed in the tube section present in the machine. After every 5 min, the cloth was removed from the machine to check out the cleaning efficiency. It was observed that after 25 min, the stains on the cloth were completely removed. This same procedure was repeated for the other two stains, but the water was changed after every performance. The fine infusion bubble's method was used for the injection of ozone produced through UV. The physico-chemical characteristics were then measured before and after each performance to find the water conditions.

2.1.3. Color removal test

The ozone process efficiency was also checked through the color removal test. The stain of ink was put on the cotton fabric cloth and then washed with the help of ozone into the machine. The cold water was used to remove the color of ink on clothes. After 25 min, it was observed that the stains of ink were removed. The above parameters were also used in this experiment to check the quality of water before and after the test [26].

2.1.4. Sterilization test

The blood, intestine fluid, and pota samples of chicken were placed on the cloths separately. The nutrient agar was prepared and then the flask, petri-dishes, and needle were placed in an autoclave for 45 min. The laminar airflow cabinet was used for streaking the bacteria on the dishes. The inner body was cleaned by using ethanol. After some time, less quantity of nutrient agar was poured into the petri-dishes to form the thin layer of nutrient agar and then wait until it would be solidified. The sterilized needle was moved on the cloth where the stains of blood were present and the streaks were drawn on the plate. This same experiment was repeated for both samples of intestine fluid and pota. These petri dishes were placed in an incubator at 37°C for 48 h and counted the bacterial colonies by using a colony counter machine. After the sterilization process, the washing process by using ozone and detergent was carried out separately. Afterward, the clothes were immediately placed into the zipper bags. The above sterilization experiment was performed again to check the bacterial removal efficiency of both ozone and detergent [27].

2.2. Analytical techniques

After the washing process, the characterization of laundry effluent was carried out to access the water pollution load. Certain physico-chemical parameters such as pH (EXTECH/PH210; Ohio, USA), electrical conductivity (EC) (EXTECH/PH210; Ohio, USA), and temperature were analyzed following the standard methods of water and wastewater [28]. The COD was measured by Tintometer (Lovibond GmbH 44287).

2.3. Reaction kinetics

The removal of stains on clothes dissolved in water goes through many reactions and it was difficult to identify these reactions individually. Therefore, the kinetic was used to assume the rate of stain removal present cloths. The equation shows the rate of first-order reaction kinetics.

$$-\frac{dC}{dt} = kC \tag{1}$$

where dC/dt is the rate of change of concentration in the sample, C is the sample concentration at time, k is the rate constant and negative sign in the formula showed that the concentration of a sample decreases with an increase in time. When $t = 0$ then the initial concentration of the sample is denoted by C_o and the time passes so the final concentration is represented by C_t. After the integration of Eq. (1):

$$\ln\frac{C_t}{C_o} = -kt \tag{2}$$

$$k = \frac{1}{t}\ln\frac{C_o}{C_t} \tag{3}$$

where C_o = initial concentration of the sample when $t = 0$; C_t = final concentration of sample at instant time (t); k = first-order rate constant at (min^{-1}); t = time of reaction expressed in min.

In these experimental analyses, the reaction kinetic (min^{-1}) is demonstrated as the first-order kinetics vs. time. It can be attributed that the correlation between $\ln(C_o/C_t)$ and oxidation time is linear, which is primarily a pseudo-first-order reaction kinetic plot [Eq. (2)].

2.4. Calculation of electrical energy consumption and cost

The consumption of electrical energy of powerful parameters such as ozone generator was determined by using Eq. (4). The electrical energy was determined in kWh and it was determined by multiplying the use of power by hours throughout the process.

$$\text{EE} = p \times t \tag{4}$$

where p = power of the electrical appliance; t = time required for operation.

In this study, the power of the ozone generator was 100 W, while the time was taken every five intervals. The cost (in rupees) was calculated when the electrical energy was multiplied by the cost per kWh. The prize for one-unit electrical energy supplied to the industrial sector of Pakistan was 19 Rs (USD 0.093).

To statistical analyze data, Microsoft Excel 2019® (Microsoft, USA), was used to calculate the standard deviation and regression line R^2. Collected data was placed in an Excel spreadsheet where graphs and tables were obtained.

3. Results and discussion

3.1. Stain removal and kinetics

Particularly, the ozonation process has been considered the feasible and viable application to treat laundry wastewater and efficiently remove the color and other physical parameters such as electrical conductivity, suspended solids, and COD. The stain removal efficiency of ozone is directly proportional to time, as retention time increases, the cleaner the cloth will be. In addition, the increased oxidation time resulted in the increasing rate of removal efficiencies with ozone treatment. After 25 min oxidation treatment, the removal efficiencies of ozone in the case of ketchup and tea were depicted at 98% and 95%, respectively because of decomposition formation reactions of hydroxyl radicals (Fig. 1). In the case of soil, its efficiency was slightly less about 86%.

In all the experiments, the tap water was used with initial pH of 7.45, electrical conductivity 1.62 mS/cm, COD 3 to 3.5 mg/L, and a temperature of 25°C. While the final concentration of all these parameters is represented in Table 1. The excessive number of ions present in laundry wastewater, which ultimately increase conductivity and deteriorate water quality. The declining trend represents that number of pollutants, dissolved solids, and dyes were removed and the ability to conduct electricity is also eliminated by the ozonation process. The rate of reaction in the stain removal of tea, ketchup, and soil is given in Fig. 2a–c, which indicates a gradual decrease in reaction rate with time. The rate of reaction was calculated for each interval using Eq. (3). In particular, the R^2 values are closer to one, which indicates the goodness of the rate of reaction and fitness of the first-order kinetic model. The fit of the model is determined by the regression coefficient R^2. Although R^2 values are apparently corrected, the relation between the reaction kinetics and time was actually non-linear based on the obtained findings.

Ozonation reduces levels of suspended solids without adding any total dissolved solids to the effluents, provides effective virus removal, and is cost-effective. The dosage of ozone (gas phase) in the current study was 10 mg/L·h. A similar study by Tanveer et al. [34] investigated that the ozonation process was used for the treatment of textile dye-bath effluents with 50 mg of optimized ozone dose. The ozone efficiency in ketchup removal was 2 times high than tea sample. The overall percentage removal of these organic stains was 98% while the efficiency of ozone in inorganic stains removal was 86% which was 5 times lower than

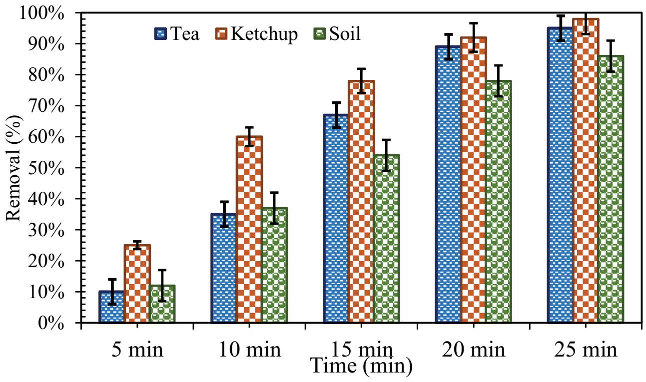

Fig. 1. Stain removal efficiency of ozone with time for tea, ketchup, and soil stains.

Table 1
Physico-chemical parameters (temperature, pH, and EC) of water after 25 min treatment

Samples	Physico-chemical parameters (After 25 min washing)		
	Temperature	pH	EC (mS/cm)
Tea	22°C ± 0.2	8 ± 0.3	0.503 ± 0.002
Ketchup	24°C ± 0.3	8.16 ± 0.01	0.821 ± 0.003
Soil	23.6°C ± 0.1	8.21 ± 0.03	0.878 ± 0.002

organic stains. Ozone has the potential to degrade the chemicals and detergents from laundry wastewater because, at alkaline conditions, decomposition rates are relatively higher [29]. Therefore, the removal rates of stains were consequently greater with increasing retention time in the ozonation process.

3.2. Decolorization analysis with kinetics

The stains of ink were used to check out the color removal efficiency of ozone. The effectiveness of ozone increased with time and reaches its maximum stage at the end. It was estimated that the ozone showed 98% efficiency in the experiment of color testing (Fig. 3). In color testing, the reaction kinetics was also calculated every 5 min, and Fig. 4 shows that the rate of reaction was high at the initial level, and it started decreasing with respect to time. Although R^2 value is apparently corrected, the relation between the reaction kinetics and time was actually non-linear based on the obtained findings (Fig. 4).

Table 2 represents the temperature, pH, and EC of water, which was being checked pre and after the treatment. The temperature and the EC of water were decreased, that is, 24.5°C and 0.894, respectively while the pH of the water was increased, that is, 7.89 after the experiment. A slight change in pH was observed, which showed that if this water is discharged directly into the water bodies, then this will not affect the marine environment. These parameters are considered very important because if these are above the standard values given by WHO then this water will affect all forms of life.

The industries of paint drying released large amounts of their wastewater into water bodies. The wastewater contained various adverse chemicals, which directly affected the environment. These compounds are mixed with water, which ultimately contaminates the water ecosystem. This study showed that due to ozone 94% of chemicals were removed from water [30]. In the current study, the ink stain removal efficiency of ozone was 98%. After the treatment, EC values showed a gradual decline and met the permissible standards.

3.3. Sterilization with ozone

The removal efficiency is shown in Fig. 5, the blood and the pota stains were completely washed in 15 min with the help of ozone while in the case of intestinal fluid the complete removal took 30 min. The rate of reaction in the sterilization process for blood, intestine, and pota samples is represented in Fig. 6a–c. Reaction kinetics were also analyzed for a comprehensive understanding of reaction mechanisms in oxidation processes. The kinetic analysis was carried out under optimal process conditions for the ozonation. At first, the reaction was rapid, but it slowed with time. Particularly, ozone, as the most powerful oxidizing reagent, is capable of degrading several pollutants effectively. Ozone was formed fine bubbles at the bottom of bowl in washing machine and converted into the dissolved form in water. The capability of ozone in the case of stains of pota and blood samples was 99% and 97%, respectively, while for intestinal fluid their efficiency was only 92%.

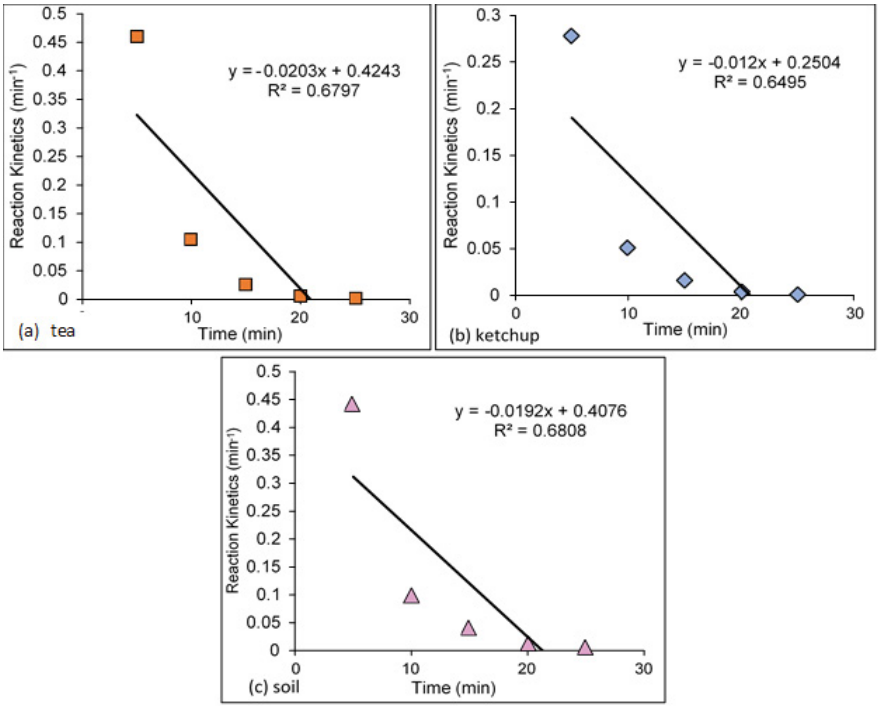

Fig. 2. Reaction kinetics with time for samples: (a) tea, (b) ketchup, and (c) soil.

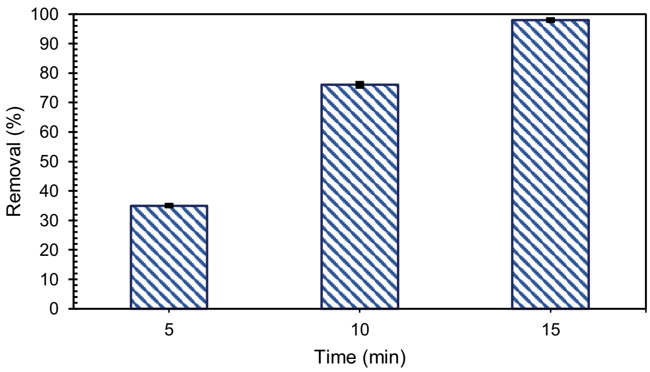

Fig. 3. Efficiency of ozone in color removal with time.

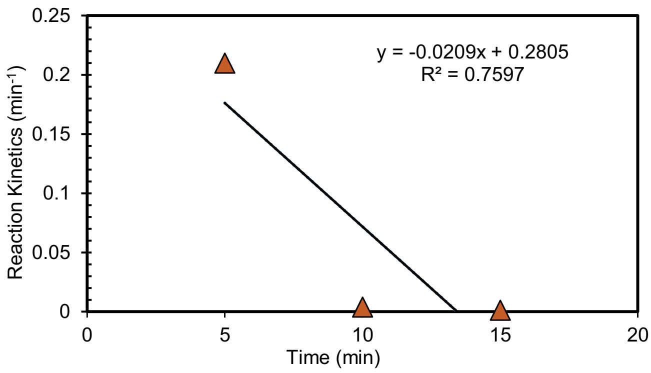

Fig. 4. Reaction kinetics for removal of ink color with time.

3.4. Sterilization with detergent

The washing process showed that the stain removal efficiency of both (detergent and ozone) was high, but in the case of bacterial removal, only ozone was efficient (Fig. 7). The removal of bacteria was 8 times higher in the case of ozone as compared to detergent. The detergent only removes a few colonies of bacteria.

The colonies of bacteria were determined by using the colony counter indicated in Table 3. Prior to washing the bacterial colonies were higher in intestine fluid as compared to others. 95% of bacterial colonies were removed with ozone while 10% were removed with detergent. In this case, the efficiency of ozone was higher as compared to detergent. The reaction kinetics was also calculated in this experiment, and it showed that with the passage of time the rate of reaction was decreased. The interval of 5 min was selected for the calculation of the reaction kinetics.

Table 2
Condition of water before and after ozone washing

Sample	Physico-chemical parameters		
Ink	Temperature	pH	EC (mS/cm)
Before washing	25°C ± 0.2	7.35 ± 0.02	1.62 ± 0.02
After 15 min wash	24.5°C ± 0.2	7.89 ± 0.02	0.894 ± 0.002

Table 4 shows the physico-chemical parameters in the case of ozone and detergent. When the ozone was used then only a slight change was observed in water but in the detergent water, the condition of water increased above the standard limits. The study was conducted in which the ozone was added to eliminate the organic compounds and compared this study with the other boiler unit in which no ozone was added. It was observed that only a significant amount of bacteria was removed, that is, 87%. In comparison to the other boiler unit where the ozone was not present showed that the level of ammonia was not decreased and only 5–6 bacteria were removed [31]. The ozone was also used to preserve beef for a long time and for this purpose a study was conducted to control the rate of microbial flora in beef. The gaseous ozone of 280 mg was then provided to the refrigerator for 5–10 min. The count of Listeria monocytogenes was also reduced when the GO was given in fewer dosages. In this study, 92% growth of microbes was also reduced [31,32].

The visual inspection (a group of five members) was conducted to check the efficiency of ozone in washing. It was determined that 4 out of 5 members confirmed the removal of organic stains with an efficiency of 98%, while the inorganic stains were not completely removed by ozone. The efficiency of ozone in inorganic stains was 5 times less than in organic stains [33,34]. In the sterilization process, the colony counter was used to determine the efficiency of both detergent and ozone in bacterial removal. The washing capability of both (ozone and detergent) was high but for bacterial removal, their efficiencies were different. In ozone, more than 95% of the bacteria in all the samples were removed while the detergent removed only a few colonies of bacteria. The ozone efficiency was 9 times more than the detergent.

3.5. Reduction in water footprint

Laundry has been considered high impact on the environment. It has a high-water footprint because a large amount of water is consumed at the domestic and industrial sectors.

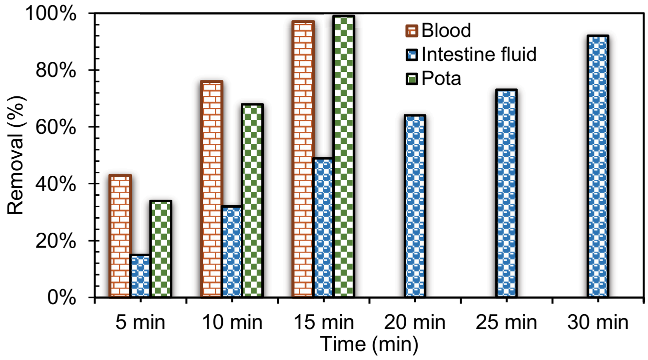

Fig. 5. Stain removal efficiency of ozone with time for chicken blood, intestinal fluid, and pota.

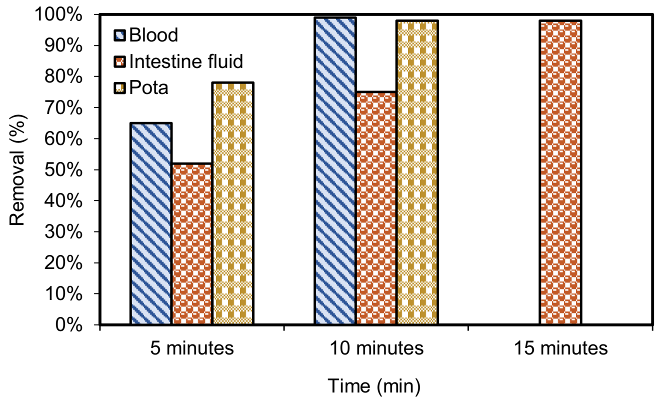

Fig. 7. Stain removal efficiency of detergent with time for blood, intestinal fluid, and pota samples.

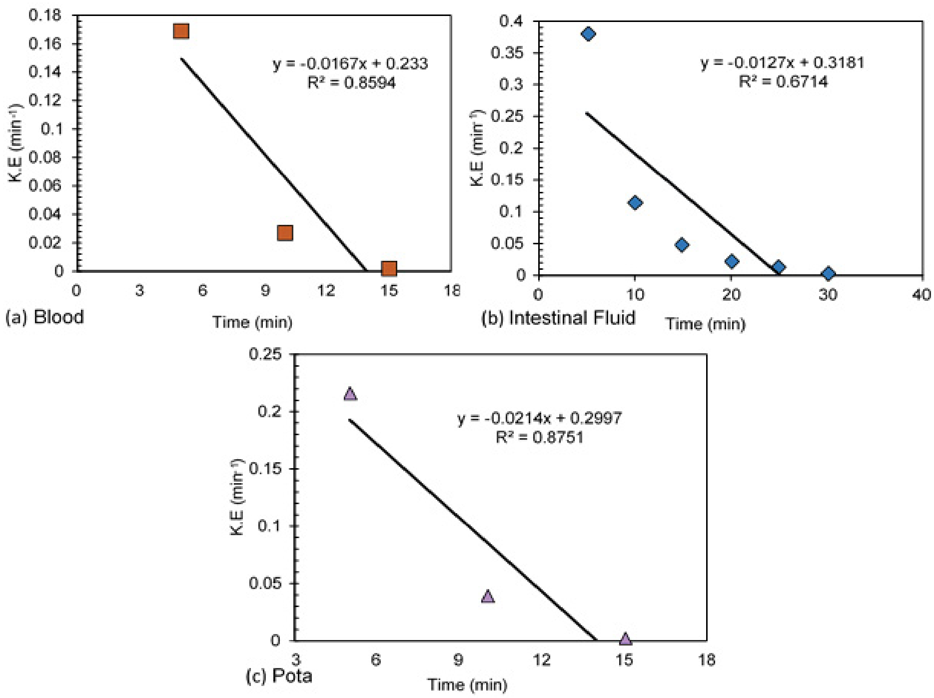

Fig. 6. Reaction kinetics (min^{-1}) for samples with time (a) blood, (b) intestinal fluid, and (c) pota samples.

Table 5 shows the water consumption of a medium-sized family in a year. A medium-sized washing machine with a 7 kg laundry load requires almost 120 L of water. To perfectly clean clothes and remove detergent remained laundry requires three wash cycles including the rinsing process. The overall consumption is 360 L of water per laundry load. An average family of four people completes almost 8 loads of laundry per week. The water consumes per week by an average family of four people will reach about 2,880 L per week. Through this water consumed in laundry per year can be calculated. For an average family laundry, water consumption will be 155, 520 L a year. This huge amount of water is consumed by just one family. At the commercial level, this value is far more. On the other hand, ozone laundry almost conserves 80%–90% water. It requires only a single step which annually consumes only 51, 840 L of water.

3.6. Reduction in detergent cost

Detergents are an important part of the laundry. Their popularity is increasing because they can be metered automatically in the washing machine and have good dispersibility in water. The sale of laundry detergent is a larger business because they are consumed when used. There are many different brand detergents in Pakistan with different. The most common and widely used brand costs almost 320 per kg (USD 1.56). According to Uniliver, the suggested amount of detergent for a single load of laundry is 110 mL. In Pakistan, the estimated detergent cost for a single-family reaches up to 15,000 PKR/y (USD 73.17). The prices are far more for the industrial sector. Ozone laundry reduces or sometimes eliminates the need for detergents. Table 6 indicates the detergent cost of a medium-sized family in Pakistan. Using 110 mL of detergent for 7 kg of clothes will cost 282 PKR per week (USD 1.38). Annually, it will cost 15,206 PKR (USD 74.17).

Detergents are widely distributed all over the world. Almost $60 annually are invested in the production of detergents. Soaps were used for cleaning; they contain fewer chemicals compared to detergent. The increasing hardness of water has replaced soap and detergent because of soap sedimentation. The main cleaning agent of detergents is a surfactant which includes chlorine bleach, enzymes, soil-suspending agent, dyes, brighteners, bacterial agents, and other raw materials. In 2014, the annual worldwide trade of surfactants was more than $33 million. Surfactants are not completely degraded in the laundry. Their release, though laundry wastewater leads to the development of massive foam in water in streams and rivers. The surfactant can only be degraded by certain microorganisms. Phosphate is also a component of detergent. It enters the water through laundry wastewater and causes eutrophication, which is the enrichment of nutrients. The bloom formed because eutrophication reduces oxygen penetration in water, and results in defective absorption of dissolved oxygen in the water.

3.7. Energy consumption and cost by ozone generator

Ozone laundry is the best way for improving water and energy efficiency for domestic and commercial laundry. It consists of an ozone generator, which generates ozone gas

Table 3
Bacterial count of the sterilization process

Samples	Raw sample	Treatment with ozone	Treatment with detergent
Blood	37	8	30
Intestine fluid	38	12	33
Pota	24	6	17

Table 4
Physico-chemical parameters of water before and after treatment with ozone and detergent

Samples	Treatment with ozone			Treatment with detergent		
	Temperature	pH	EC	Temperature	pH	EC
Blood	24.5°C ± 0.2	8.12 ± 0.2	1.23 ± 0.6	27°C ± 0.3	10.6 ± 0.2	2.07 ± 0.02
Intestine fluid	23°C ± 0.3	7.84 ± 0.2	1.08 ± 0.5	26.2°C ± 0.3	11.4 ± 0.1	2.28 ± 0.02
Pota	22°C ± 0.3	8.02 ± 0.2	1.17 ± 0.02	28°C ± 0.3	11.8 ± 0.1	2.16 ± 0.02

Table 5
Water consumption for a medium size family per year

Water consumption (in L) by a medium size family 1 y						
Laundry load	Water consumption	Cycle required	Water per load	Laundry load/week	Water per week	Water per year
Traditional laundry						
7 kg	120	3	360	8	2,880	155,520
Ozone laundry						
7 kg	120	1	120	8	960	51,840

Table 6
Cost of detergent for a medium family per year

Detergent cost (surf excel) in PKR for a medium size family 1 y						
Laundry load	Detergent required per load	Price per mL	Price per load	LL per week	Price per week	Price per year
Traditional laundry						
7 kg	110 mL	0.32	35	8	282	15,206
Ozone laundry						
7 kg	–	–	–	8	–	–

Table 7
Cost and energy consumption for 100 W ozone generator

Energy consumed (in kWh) and cost (in PKR) by a 100 W ozone generator in a year							
Laundry load	Energy per load	Laundry load per week	Energy per week	Energy per year	Unit price	Cost per week	Cost per year
7 kg	0.174	8	1.392	75.17	19	24.44	1,428

Table 8
Calculation of electrical energy and cost for 30 min

Treatment process	Time (min)	Electrical energy (kWh)	Cost (PKR)
Ozone generator	5	0.0083	0.1577
	10	0.033	0.627
	15	0.016	0.304
	20	0.042	0.798
	25	0.025	0.475
	30	0.05	0.95

from ambient air and injects it into the water. When dissolved in water, it opens fibers and releases strains. Opening fibers make it easy to dry linen, thus reducing drying time. Table 7 shows the energy consumption and the related costs of a 100 W ozone generator. It consumes 0.174 kWh of energy per laundry load of 7 kg. If a family performs 8 loads per week, then the electricity cost of an ozone generator will be 24.44 PKR (USD 0.12). Annually it will consume 75 kWh of energy which will cost 1,428 PKR (USD 6.97). Industries and other commercial sector can save a lot of energy and water. Dryers are an important part of domestic and commercial laundry. As ozone opens fabric this will reduce the cost of drying and save a huge amount of energy. Table 8 depicts the electrical energy consumption values for 30 min.

4. Conclusions and future outlook

In this study, the experimental design was carried out by performing the sample containing organic, inorganic, and microbial contamination, and the results are compared to the traditional method of laundry. Ozone was found 9 times more efficient in cleaning different stains and killing microbes. The first phase of the trial was on organic components in which ketchup and tea stains were tested. Ozone cleaned both in the very short wash cycle, keeping all water quality parameters normal. The second phase was on inorganic stains of soil. Ozone showed significant performance in removing dirt from clothes by keeping all water quality parameters normal. This is the only phase, which has taken more than 15 min. In the third phase, ozone's effectiveness in sterilizing clothes was tested. Different contaminant samples of chicken blood, intestinal fluids, and fecal material were tested. Ozone killed 95% of all microbes in just 15 min of wash time.

Due to its uniqueness, its applications are wide and further research and development can bring important breakthroughs. Pakistan as a developing country is faced with economic and environmental issues. The methods which are used for laundry are quite old and have little effectiveness. The small-scale experiment was quite successful, and it widens the opportunities in Pakistan to implement it on a commercial scale. Industries in Pakistan involve huge labor and commoner contaminates found on workers, laundry is skin secretion. To clean their laundry industries used a large amount of warm water and detergent which require lots of energy. Through ozone laundry, both large- and small-scale industries can achieve benefits in terms of cost reduction and environmental protection. Further research can include actual samples from hospital, industrial and domestic sectors. Future studies can include SARS-Cov-2 infected laundry to check its efficiency in sterilization. The efficiency of ozone in sterilizing human blood and various bacteria found in the human body can be tested in the future.

References

[1] M.A. Iribarnegaray, M.S. Rodriguez-Alvarez, L.B. Moraña, W.A. Tejerina, L. Seghezzo, Management challenges for a more decentralized treatment and reuse of domestic wastewater in metropolitan areas, J. Water Sanit. Hyg. Dev., 8 (2017) 113–122.

[2] S.A. Mousavi, F. Khodadoost, Effects of detergents on natural ecosystems and wastewater treatment processes: a review, Environ. Sci. Pollut. Res., 26 (2019) 26439–26448.
[3] Z.M. Yaseen, T.T. Zigale, Tiyasha, D. Ravi Kumar, S.Q. Salih, S. Awasthi, T.M. Tung, N. Al-Ansari, S.K. Bhagat, Laundry wastewater treatment using a combination of sand filter, bio-char and teff straw media, Sci. Rep., 9 (2019) 18709, doi: 10.1038/s41598-019-54888-3.
[4] K.C. Ho, Y.H. Teow, J.Y. Sum, Z.J. Ng, A.W. Mohammad, Water pathways through the ages: integrated laundry wastewater treatment for pollution prevention, Sci. Total Environ., 760 (2021) 143966, doi: 10.1016/j.scitotenv.2020.143966.
[5] S. De Gisi, P. Casella, C.M. Cellamare, M. Ferraris, L. Petta, M. Notarnicola, Wastewater reuse, Encycl. Sustain. Technol., 4 (2017) 53–68.
[6] O. Lade, Z. Gbagba, Sustainable water supply: potential of recycling laundry wastewater for domestic use, J. Civ. Eng. Environ. Sci., 26 (2017) 56–60.
[7] K.N. Sheth, M. Patel, M.D. Desai, A study on characterization & treatment of laundry effluent, Int. J. Innov. Res. Sci. Technol., 4 (2017) 50–55.
[8] J. Luo, Q. Zhang, L. Wu, Q. Feng, F. Fang, Z. Xue, C. Li, J. Cao, Promoting the anaerobic production of short-chain fatty acids from food wastes driven by the reuse of linear alkylbenzene sulphonates-enriched laundry wastewater, Bioresour. Technol., 282 (2019) 301–309.
[9] V.V. Patil, P.R. Gogate, A.P. Bhat, P.K. Ghosh, Treatment of laundry wastewater containing residual surfactants using combined approaches based on ozone, catalyst and cavitation, Sep. Purif. Technol., 239 (2020) 116594, doi: 10.1016/j.seppur.2020.116594.
[10] M. Oteng-Peprah, M.A. Acheampong, N.K. deVries, Greywater characteristics, treatment systems, reuse strategies and user perception—a review, Water Air Soil Pollut., 229 (2018) 255, doi: 10.1007/s11270-018-3909-8.
[11] A.C. Kogawa, B.G. Cernic, L.G.D. do Couto, H.R.N. Salgado, Synthetic detergents: 100 years of history, Saudi Pharm. J., 25 (2017) 934–938.
[12] H.F.R. Schröder, H.J. José, W. Gebhardt, R.F.P.M. Moreira, J. Pinnekamp, Biological wastewater treatment followed by physico-chemical treatment for the removal of fluorinated surfactants, Water Sci. Technol., 61 (2010) 3208–3215.
[13] K.Z. Benis, A. Behnami, E. Aghayani, S. Farabi, M. Pourakbar, Water recovery and on-site reuse of laundry wastewater by a facile and cost-effective system: combined biological and advanced oxidation process, Sci. Total Environ., 789 (2021) 148068, doi: 10.1016/j.scitotenv.2021.148068.
[14] D.I. Kern, R. de O. Schwaickhardt, G. Mohr, E.A. Lobo, L.T. Kist, Ê.L. Machado, Toxicity and genotoxicity of hospital laundry wastewaters treated with photocatalytic ozonation, Sci. Total Environ., 443 (2013) 566–572.
[15] O. Fónagy, E. Szabó-Bárdos, O. Horváth, G. Kiss, Application of ozonation and silveration for heterogeneous photocatalytic degradation of an aromatic surfactant, J. Photochem. Photobiol., A, 366 (2018) 152–161.
[16] E.T. Wahyuni, R. Roto, M. Sabrina, V. Anggraini, N.F. Leswana, A.C. Vionita, Photodegradation of detergent anionic surfactant in wastewater using UV/TiO_2/H_2O_2 and UV/Fe^{2+}/H_2O_2 processes, Am. J. Appl. Chem., 4 (2016) 174–180.
[17] M. Ghaderpoori, M.H. Dehghani, Investigating the removal of linear alkyl benzene sulfonate from aqueous solution by ultraviolet irradiation and hydrogen peroxide process, Desal. Water Treat., 57 (2016) 15208–15212.
[18] K. Kuźmiński, A.W. Morawski, M. Janus, Adsorption and photocatalytic degradation of anionic and cationic surfactants on nitrogen-modified TiO_2, J. Surfactants Deterg., 21 (2018) 909–921.
[19] T. Razavi, A. Fadaei, M. Sadeghi, S. Shahsavan markadeh, Study of the impact of combination of ZnO nanoparticles with ultraviolet radiation (photocatalytic process) on the removal of anionic surfactant linear alkyl benzene sulfonate (LAS) from aqueous solutions using Taguchi statistical method, Desal. Water Treat., 57 (2016) 28755–28761.
[20] M.B. Miranzadeh, R. Zarjam, R. Dehghani, M. Haghighi, H.Z. Badi, M.A. Marzaleh, A.M. Tehrani, Comparison of Fenton and photo-Fenton processes for removal of linear alkyle benzene sulfonate (Las) from aqueous solutions, Pol. J. Environ. Stud., 25 (2016) 1639–1648.
[21] A.J. Barik, P.R. Gogate, Degradation of 2,4-dichlorophenol using combined approach based on ultrasound, ozone and catalyst, Ultrason. Sonochem., 36 (2017) 517–526.
[22] E.M. Cuerda-Correa, M.F. Alexandre-Franco, C. Fernández-González, Advanced oxidation processes for the removal of antibiotics from water: an overview, Water, 12 (2020) 102, doi: 10.3390/w12010102.
[23] S.N. Malik, P.C. Ghosh, A.N. Vaidya, S.N. Mudliar, Hybrid ozonation process for industrial wastewater treatment: principles and applications: a review, J. Water Process Eng., 35 (2020) 101193, doi: 10.1016/j.jwpe.2020.101193.
[24] W.N. Agosto, Dual-Use Space Technology Transfer Conference and Exhibition, Conference Proceedings, 2013. Available at: https://ntrs.nasa.gov/citations/19960022615
[25] J. Wang, Z. Bai, Fe-based catalysts for heterogeneous catalytic ozonation of emerging contaminants in water and wastewater, Chem. Eng. J., 312 (2017) 79–98.
[26] M.İ. Bahtiyari, H. Benli, Comparison of ozone-based cold bleaching processes with conventional pretreatment of cotton, Ozone Sci. Eng.: The J. Int. Ozone Assoc., 42 (2020) 450–460.
[27] R.G. Rice, M. DeBrum, D. Cardis, C. Tapp, The ozone laundry handbook: a comprehensive guide for the proper application of ozone in the commercial laundry industry, Ozone Sci. Eng.: The J. Int. Ozone Assoc., 31 (2009) 339–347.
[28] R.B. Baird, A.D. Eaton, E.W. Rice, Eds., Standard Methods for the Examination of Water and Wastewater, 23rd ed., American Public Health Association, American Water Works Association, Water Environment Federation, Washington D.C., 2017.
[29] C.G. Joseph, Y.Y. Farm, Y.H. Taufiq-Yap, C.K. Pang, J.L. Nga, G.L. Puma, Ozonation treatment processes for the remediation of detergent wastewater: a comprehensive review, J. Environ. Chem. Eng., 9 (2021) 106099, doi: 10.1016/j.jece.2021.106099.
[30] J.M. Alvarez, C.J. Seijas, G.L. Bianchi, Elimination of volatile organic compounds in paint drying by absorption reaction in water combined with the ozone oxidation technique, Environ. Adv., 2 (2020) 100017, doi: 10.1016/j.envadv.2020.100017.
[31] P.N. Humphreys, J. Hook, S. Rout, Evaluation of the cleaning efficiency of microfibre cloths processed via an ozonated laundry system, J. Infect. Prev., 13 (2012) 104–108.
[32] R. Tanveer, A. Yasar, H. Nissar, Amt-ul-Bari Tabinda, A.-S. Nizami, Energy efficiency of the advance physical system for the complete treatment of dye-bath effluents, Desal. Water Treat., 237 (2021) 271–283.
[33] B. Giménez, N. Graiver, L. Giannuzzi, N. Zaritzky, Treatment of beef with gaseous ozone: physico-chemical aspects and antimicrobial effects on heterotrophic microflora and listeria monocytogenes, Food Control, 121 (2021) 107602, doi: 10.1016/j.foodcont.2020.107602.
[34] R. Tanveer, A. Yasar, Amt-ul-Bari Tabinda, A. Ikhlaq, H. Nissar, A.-S. Nizami, Comparison of ozonation, Fenton, and photo-Fenton processes for the treatment of textile dye-bath effluents integrated with electrocoagulation, J. Water Process Eng., 46 (2022) 102547, doi: 10.1016/j.jwpe.2021.102547.