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ELECTROCOAGULATION SYSTEM FOR TREATMENT OF BALLAST WATER

Irwan EFFENDI[1], Muhammad Fadil GHIFARI[1*], Syahril NEDI[1], & Sania EFFENDI[2]

[1]*Faculty of Fisheries and Marine Sciences, University of Riau, Indonesia.*
[2]*School of Vocation, University of Gajah Mada, Yogjakarta, Indonesia.*
**Corresponding author: mfadilghifarii@gmail.com*

Abstract: This study aimed to determine the removal of hazardous materials in ballast water by using an electrocoagulation (EC) system. This research was carried out on January 16 – June 15 2023 in Batam City. Ballast water was supplied by tanker ships anchored at 5 ports in Batam Island, namely Batam Centre, Sekupang, Nongsapura, Telaga Punggur, and Batu Ampar. The ballast water was collected and processed through an electrocoagulation system at PT. Batam Air Cargo Village, Batam. Meanwhile, the quality of the treated ballast water was examined by PT. Mutuagung Lestari Batam, Batam, Indonesia. If the laboratory test results meet the requirements, then the remaining ballast water can be disposed of into nature. However, if the test results are not met, then the ballast water is re-processed and channeled to the mixing tank. The physical parameters of the treated ballast water showed a temperature of 28ºC, total dissolved solids (TDS), and total suspended solids (TSS) of around 140 and 11 mg/L respectively. The main heavy metal content of ballast water after the electrocoagulation process showed cadmium (< 0.001 mg/L), chrome (< 0.02 mg/L), mercury (< 0.0001 mg/L), lead (< 0.005 mg/L), copper (0.14 mg /L), zinc (0.31 mg/L), and arsenic (< 0.0001 mg/L). The physical parameters of the treated ballast water showed a temperature of 28ºC, total dissolved solids (TDS), and total suspended solids (TSS) of around 140 and 11 mg/L respectively. The main heavy metal content of ballast water after the electrocoagulation process showed cadmium (< 0.001 mg/L), chrome (< 0.02 mg/L), mercury (< 0.0001 mg/L), lead (< 0.005 mg/L), copper (0.14 mg /L), zinc (0.31 mg/L), and arsenic (< 0.0001 mg/L). Other chemical and biological parameters that were also measured included sulfide (< 0.002 mg/L), fluoride (0.11 mg/L), chlorine (0.05 mg/L), ammonia (0.78 mg/L), nitrate (< 0.05 mg/L), nitrite (< 0.004 mg/L), total nitrogen (0.78 mg/L), BOD5 (22.69 mg/L), methylene blue active compound (0.732 mg/L), phenol (0.001 mg/L), oil and fat (1.032 mg/L), pH (7.13), and total coliform (615 MPN/100). All parameters showed that the hazardous content of electrocoagulated ballast water waste has met the quality standards for ballast water waste. It has also been tested to process other liquid waste. So, it is very promising to be developed for other waste processing needs in the future.

Keywords: ballast water nutrient, ballast water quality standards, heavy metals, seawater pollution, total dissolved solids, total suspended solids.

1. INTRODUCTION

Ballast water refers to the water that is deliberately loaded into ships to provide stability and balance, particularly when they are not fully loaded with cargo. Ships take on ballast water in one location and release it in another, often spanning international borders. While ballast water serves a crucial purpose for the safe operation of vessels, it can also be a significant vector for the spread of invasive species (Lakshmi et al., 2021). The issue arises when organisms from one region are taken up in the ballast water and then released into a different ecosystem at the ship's destination. These introduced species can outcompete native species and disrupt local ecosystems. Water ballast may have the potential to cause harm to human health or the environment due to its toxic or poisonous nature. These materials may include chemicals, gases, or substances that, when released or exposed to living organisms, can lead to adverse effects, and led to various environmental and economic problems (Bradie et al., 2023).

The International Maritime Organization (IMO) has introduced the International Convention for the Control and Management of Ships' Ballast Water and Sediments to address the environmental concerns associated with ballast water. The convention aims to prevent, minimize, and ultimately eliminate the transfer of harmful aquatic organisms and pathogens through the control and management of ships' ballast water and sediments (Chen et al., 2023). Ships are required to follow certain standards and procedures, such as treating ballast water to remove or kill organisms before discharge, to reduce the ecological impact of ballast water movements. The implementation of these measures helps protect marine ecosystems and biodiversity (Bailey et al., 2022).

Electrocoagulation is a water treatment process that utilizes an electrical current to destabilize and remove suspended and dissolved contaminants from water. When applied to ballast water treatment on ships, it is referred to as an Electrocoagulation System for Ballast Water. Electrodes: The system consists of electrodes, usually made of materials like aluminum or iron, which are immersed in the ballast water. Electrolysis: When an electrical current is applied to the electrodes, metal ions are released into the water. These ions can act as coagulants. Coagulation: The released metal ions destabilize and coagulate suspended particles, such as algae, bacteria, and other impurities in the ballast water. These contaminants clump together into larger particles. Flocculation: The coagulated particles form flocs, which can be easily separated from the water. Separation: The flocs are then removed from the water through processes like settling or filtration. The system can effectively treat ballast water and remove a variety of contaminants, including potentially harmful microorganisms (Jovanović et al., 2021).

The electrocoagulation system is considered environmentally friendly because it avoids the use of chemical additives and minimizes the risk of introducing new substances into the treated water (Youssef, 2021; Rahman et al., 2021). The process helps ships comply with these regulations and prevent the introduction of invasive species, removing suspended particles, sediments, and other impurities from ballast water (Shahedi et al., 2020). However, it is very necessary to measure the results of this electrocoagulation system in reducing waste levels in ballast water. This figure will be the basis for the decision of whether ballast wastewater can be discharged into the environment or not. This research aimed to determine the effectiveness of an electrocoagulation system on ballast water waste by taking samples processed by PT. Batam Air Cargo Village, Batam, Indonesia.

2. METHODOLOGY

2.1 Time and place

This research was carried out on January 16 – June 15 2023 in Batam City. Ballast water was supplied by tanker ships anchored at 5 ports in Batam Island, namely Batam Centre, Sekupang, Nongsapura, Telaga Punggur, and Batu Ampar. The ballast water was collected and processed at PT. Batam Air Cargo Village, Batam. Meanwhile, the quality of the treated ballast water was examined by PT. Mutuagung Lestari Batam, Batam, Indonesia.

2.2 Research methodology

By using survey method, primary data was obtained from the two companies above (PT. Batam Air Cargo Village and PT. Mutuagung Lestari Batam). Meanwhile, secondary data was obtained from several other scientific reading sources.

2.3 Research procedure

Ballast water is transferred into the oil & sludge tramp tank (volume of 1,000 m^3) to separate the sludge layer from the oil using the settling method. The settled sludge and oil are stored in the waste deposit tank (volume of 300 m^3). This waste can be used for other uses. The remaining ballast water is then flowed into mixing tanks (volume of 3.0m^3) for 5 minutes. Next, this waste is transferred into reactor tanks (each with a volume of 1.0m^3). Each reactor tank contains 22 aluminum plates as the anode and cathode poles. Each tub is powered by 20 volts of DC electricity. The electrocoagulation process lasts for 1 hour. Next, the ballast water is channeled into sludge settling tanks (lamellas), each with a volume of 5.0 m^3) for 30 minutes. Lamella can also function as a temporary shelter. Periodically the sediment will be harvested and stored in a waste deposit. Next, the ballast water is channeled into a filter tank (filter press). The filter press functions to filter solids that are still contained in waste water and at the same time provide it through the compressor to form cake/sludge. Sludge or cake is collected to be used for other industrial needs. The remaining ballast water is then stored in temporary storage tanks (holding tanks), each with a volume of 1.4 m^3. Storage time ranges from 1-3 days. This material is then channeled into carbon filters (each volume 6 m^3). In the carbon filter, wastewater will flow through activated carbon. The filtered liquid is then flowed into the final holding tanks (each volume 20 m^3). The storage time ranges from 1-7 days, which depends on the results of the sample examination by PT. Mutuagung Lestari Batam who carries out the wastewater quality checking process. If the laboratory test results on the samples meet the requirements, then the remaining ballast water can be disposed of into nature (disposal) or temporarily stored in a disposal tank. However, if the test results are not met, then the ballast water is re-processed and channeled to the mixing tank. The flow chart of all these processes is presented in Figure 1.

2.4 Ballast water parameters

Ballast water quality parameters measured included physical parameters (temperature of total dissolved solids and total suspended solid), the content of some heavy metals (iron, manganese, barium, copper, zinc, chrome, total chrome, cadmium, mercury, lead, stannum, arsenic, selenium, nickel, cobalt, cyanide, and fluoride), and other chemical parameters (sulfide, chlorine, ammonia, nitrate, nitrite, total nitrogen, biological oxygen demand, and pH). Examination of ballast water quality parameters was carried out by another company, namely PT. Mutuagung Lestari Batam. This examination method refers to INS (2008), MER (2014), and Rice & Bridgewater (2012).

2.5 Data analysis

In this research, as a ballast water waste management company, PT. Batam Air Cargo Village focuses its attention on ballast water parameters after electrocoagulation treatment. First, they received orders for ballast water electrocoagulation treatment from various companies. They collected this ballast water, mixed it, and then processed it. Thus, initial ballast water data per company and arrival date are not available. For this reason, the author took ballast water data from several references. Then it is compared with data on water quality parameters resulting from the electrocoagulation process. These results have recently been referred to the standard standards issued by the Indonesian Government and the quality standards issued by the world body that manages this matter. The data obtained were analyzed and discussed descriptively regarding existing literature.

3. RESULTS AND DISCUSSIONS

3.1 Physical parameters of ballast water

In this study, generally, ballast water before processing physically looked cloudy and had a dark black color. This color is closely related to the presence of pollutants in the wastewater itself (Figure 2). After going through several stages, the wastewater that comes out of the filter press process looks much clearer than before, but the color of the water itself still looks a little yellow. For this reason, it is necessary to carry out further filtration in a filter press, where wastewater is obtained which looks clearer than before and there is a visible pile of waste

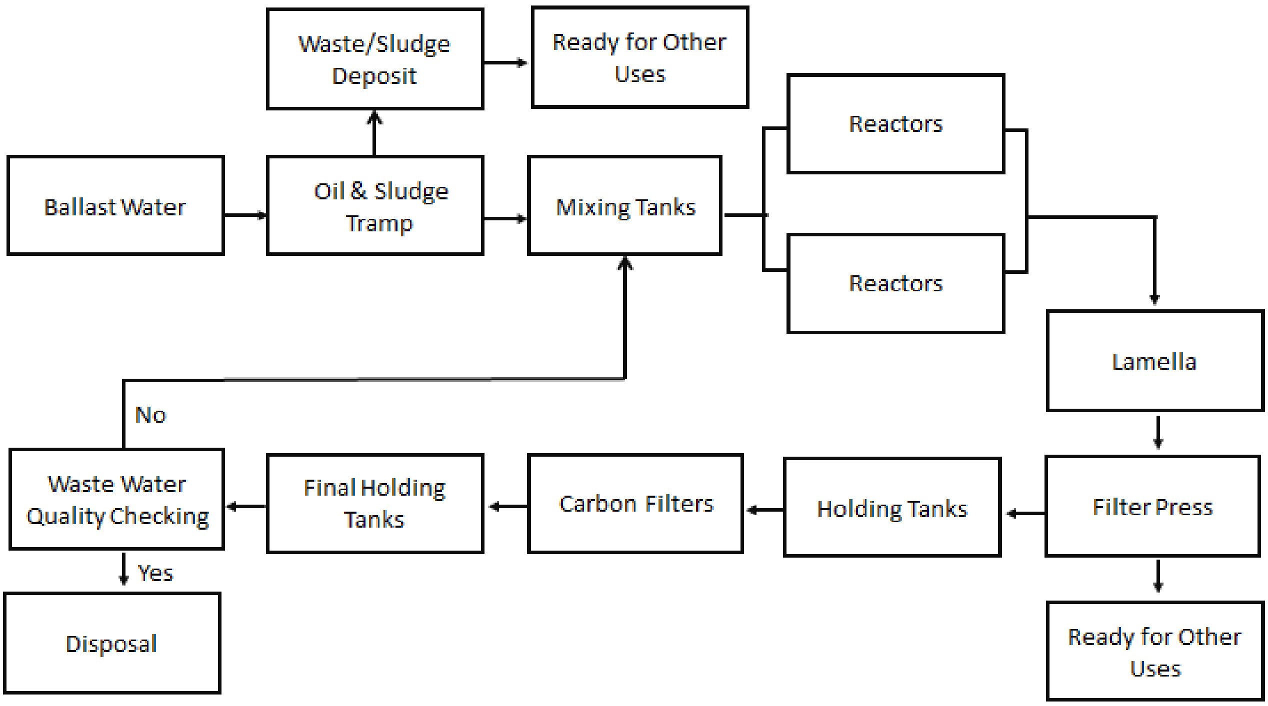

Figure 1. Flow chart of the ballast water processing process at PT. Batam Air Cargo Village, Indonesia.

Figure 2. Ballast water before the electrocoagulation process.

Figure 3. Ballast water sludge deposits after the sedimentation process.

Figure 4. Ballast water after the electrocoagulation and filtering process

Figure 5. Sludge or ballast water residual cake in the filter press tank.

at the bottom of the vessel (Figure 3). After passing through the sedimentation stage, a pile of waste can be noted forming at the bottom of the vessel (Figure 4). This wastewater then enters the filtration stage to separate the solid and liquid waste that has been processed. Waste water goes through a filter press process first. After the filter press process is carried out, the resulting residue is in the form of sludge/cake (Figure 5). Then, after going through the filter press process, the wastewater will then flow to the carbon filter. Similar results have been reported by researchers from several places. For example, Larue et al., (2003), Holt et al., (2005), and Sivakumar et al., (2004) reduced the turbidity of some liquid waste by using batch-floated and settled methods.

Electrocoagulation is a water treatment process that uses an electric current to remove contaminants, including suspended solids, metals, and microorganisms, from water. This technique has been explored for ballast water treatment to comply with international regulations aimed at preventing the spread of invasive species through ship ballast water discharge (Ulucan et al., 2014). The electrocoagulation process involves the following steps. Typically, two electrodes are immersed in the ballast water. One electrode is the anode (positive), and the other is the cathode (negative). When a direct current is applied across the electrodes, electrolysis occurs in the water. This process generates metal hydroxide flocs (coagulants) at the anode (Sahu et al., 2014). The metal hydroxide flocs act as coagulants that neutralize and destabilize the charged particles in the water. The destabilized particles start to aggregate and form larger flocs. The destabilized and coagulated particles further collide and combine to form larger aggregates called flocs. These flocs can trap suspended solids, microorganisms, and other contaminants. The formed flocs settle down due to gravity or can be separated by other physical methods, such as filtration. Once settled, the treated water can be discharged, and the separated solids are removed from the system (Rahmadyanti & Febriyanti, 2020; Saleh et al., 2022).

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Ballast water that has been treated in the electrocoagulation process was then examined in the laboratory to ensure that the physical parameters of this wastewater comply with predetermined quality standards. If the requirements have been met, the ballast water is then discharged directly into the environment. However, if it does not meet the applicable standards, the waste is transferred back to the mixing tank for reprocessing. In this study, several physical parameters tested met the requirements, where water temperature (28°C), total dissolved solid (TDS) and total suspended solid (TSS) were around 140 and 11 mg/L respectively. This figure looks very far from the initial parameters and levels before electrocoagulation was carried out. This means that electrocoagulation technology works very effectively in reducing waste levels in water ballast. This figure appears to meet the requirements for waste to be subsequently disposed of in nature. Waste quality standards (MER, 2014, Rice & Bridgewater, 2012) require threshold figures of 38 and 30°C for temperature, 2,000 and 4,000 mg/L for TDS, and 200 and 400 mg/L for TSS, respectively (Table 1).

Statistical analysis shows that the standard deviation of the data ranges between 0.950-2.081 and the variance ranges between 0.903-4.333. This shows that the temperature, TDS, and TSS parameter data are relatively uniform and normally distributed. The results of the skewness test show that the temperature, TDS, and TSS data are relatively negative, meaning that the data is distributed relatively to the left. This is following the analysis of kurtosis values, where the values are all 0.00 or <3 (platykurtic curve), meaning that the data is distributed tending to the left (Table 2).

Total dissolved solids (TDS) refers to the total amount of inorganic and organic substances dissolved in water. It includes minerals, salts, metals, cations, and anions that are present in water in a dissolved form. It is an important parameter in water quality assessment and can affect the taste, odor, and overall suitability of water for various purposes (Jang et al., 2020). The connection between TDS and ballast water lies in the fact that ballast water, when taken on in one location and discharged in another, may also carry dissolved solids from the source region to the destination region. This transfer of water and its dissolved constituents can have ecological implications, as it may introduce new chemical compositions to the receiving waters (Lee et al., 2017).

Table 1. Physical parameters of ballast water waste before and after electrocoagulation.

No.	Parameter	Unit	Before coagulation*	After coagulation	Quality Standards 1	Quality Standards 2
1.	Temperature	^oC	25 (Wu et al., 2019)	S1: 27.8 S2: 29.8 S3: 28.7 AV: 28.766	38.00	30.00
2.	TDS	mg/L	647.000-88.000 (Wu et al., 2019)	S1: 138 S2: 142 S3: 141 AV: 140.333	2000	4000
3.	TSS	mg/L	850-1.105 (Wu et al., 2019)	S1: 11.500 S2: 10.500 S3: 12.400 AV: 11.466	200	400

*Cited from some references. Quality Standards 1: MER (2014). Quality Standards 2: Rice & Bridgewater (2012). TDS: total dissolved solid. TSS: total suspended solid. S = sample. AV = average.

Table 2. Statistical analysis of temperature, TDS, and TSS parameters of ballast water landed in Batam, Indonesia.

	Minimum	Maximum	Mean		SD	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Temp.	27.80	29.80	28.766	0.57831	1.001	1.003	0.298	1.225	0.000	0.000
TDS	138.00	142.00	140.333	1.20185	2.081	4.333	-1.293	1.225	0.000	0.000
TSS	10.50	12.40	11.467	0.548	0.950	0.903	-0.158	1.225	0.000	0.000

SD= standard deviation

Total suspended solids (TSS) refers to the concentration of particles that are suspended in water and do not settle at the bottom over time. These particles can include silt, clay, organic matter, and other fine solids. High TSS levels in water can affect water clarity, and light penetration, and may have environmental implications, especially if the suspended solids contain contaminants. The connection between TSS and ballast water is that ballast water, depending on its source, may contain suspended solids. When this water is discharged in a new location, it can introduce suspended particles to that ecosystem, potentially affecting water quality. This can be a concern if the suspended solids contain pollutants or if the introduction of foreign particles disrupts the balance of the receiving water body (Jang et al., 2020).

Regulations and guidelines have been developed globally to address the issue of ballast water management. The International Maritime Organization (IMO) has established the International Convention for the Control and Management of Ships' Ballast Water and Sediments to mitigate the environmental risks associated with the transfer of ballast water. This includes measures to minimize the transfer of harmful aquatic organisms and pathogens, as well as addressing potential water quality issues such as TDS and TSS. The discharge of ballast water can contribute to the transfer of dissolved solids between different water bodies, highlighting the importance of proper ballast water management to protect marine ecosystems (Lemessa et al., 2013). Similar results have been noted by some researchers. For example, Islam et al., (2011) reported a reduction in values of TDS, alkalinity, salinity, and Cl- in treated effluents of some liquid waste in Bangladesh. If we look at the physical parameters (temperature, TDS, and TDS) of ballast water waste before and after electrocoagulation, the electrocoagulation system has been able to reduce the level of ballast water waste far below the minimum quality standards. This opinion feels more convincing if we compare the TDS and TSS levels in untreated ballast water (Wu et al., 2019). This figure appears to be far above the TDS and TSS levels obtained in this research.

3.2 Heavy metals content of ballast water

As with physical parameters, ballast water that has been treated in the electrocoagulation process is examined in the laboratory to ensure that the chemical parameters of this ballast water comply with predetermined quality standards (MER, 2014; Rice & Bridgewater, 2012). If it meets the requirements, then the ballast water is discharged directly into the environment. However, if it does not meet the applicable standards, the waste is transferred back to the mixing tank for reprocessing. The results of measuring the main heavy metal content parameters of ballast water after electrocoagulation showed the numbers for cadmium (< 0.001 mg/L), chrome (< 0.02 mg/L), mercury (< 0.0001 mg/L), lead (< 0.005 mg/L), copper (0.14 mg/L), zinc (0.31 mg/L), and arsenic (< 0.0001 mg/L). Based on the initial levels of water quality, it can be seen that electrocoagulation is quite effective in removing heavy metals contained in ballast water (Table 3).

Statistical analysis shows that the standard deviation of the data ranges between 0.00001-0.002082 and the variance is around 0.000. This shows that the data on heavy metal levels contained in ballast water are relatively uniform and normally distributed. The skewness test results show that the heavy metal content data for ballast water ranges from -1.732-1.732, meaning that the data is distributed relatively in the middle. This is following the analysis of kurtosis values, where the values are all 0.00 or < 3 (leptokurtic curve), meaning that the data is spread tending to the right and left (Table 4).

The reduction of hazardous materials in liquid waste has been known for a long time. This liquid waste varies, from urban waste, factory waste, and detergent waste to ballast water waste. Poon (1997) reduced groundwater contaminants of Ni, Zn, Cu, and Pb, to 96% by using batch and continuous system of electrocoagulation systems. Balasubramanian and Madhavan (2001) and Kumar et al., (2004) removed arsenic compounds up to 95-99 % by using a beaker glass electrocoagulation system. Similar results were also reported by Hansen et al., (2005), Gao et al., (2005), and Parga et al., (2005) reported the removal of arsenic contents of liquid waste up to 80-98, 80-97, and 99 % by using continuous EC system. Park et al., (2002), and Ninova (2003) succeeded in eliminating Cadmium 80-90 % and Cu, Zn up to 88 % from some liquid wastes, respectively.

Table 3. Heavy metal levels of ballast water before and after electrocoagulation.

No.	Parameter	Unit	Before coagulation*	After coagulation	Quality Standards 1	Quality Standards 2
1.	Iron (Fe)	mg/L	0,19-0,2 (Wu et al., 2019)	S1: 0.841 S2: 0.831 S3: 0.828 AV: 0.833	5	10
2.	Manganese (Mn)	mg/L	1.0-4 9 (Murphy et al., 2004)	S1: 0.092 S2: 0.089 S3: 0.091 AV: 0.090	2	5
3.	Barium (Br)	mg/L	1-4(Murphy et al., 2004)	S1: 0.101 S2: 0.105 S3: 0.104 AV: 0.103	2	3
4.	Copper (Cu)	mg/L	0,02-0,02 (Wu et al., 2019)	S1: 0.144 S2: 0.143 S3: 0.142 AV: 0.143	2	3
5.	Zinc (Zn)	mg/L	0,12-0,16 (Wu et al., 2019)	S1: 0.322 S2: 0.312 S3: 0.311 AV: 0.315	5	10
6.	Chrome (Cr^{6+})	mg/L	1.13-6.33 (Dobaradaran et al., 2018)	S1: 0.021 S2: 0.018 S3: 0.027 AV: 0.022	0.1	0.5
7.	Total Chrome (Cr)	mg/L	1.13-6.28 (Dobaradaran et al., 2018)	S1: 0.086 S2: 0.078 S3: 0.082 AV: 0.082	0.5	1
8.	Cadmium (Cd)	mg/L	1,076-2,457 (Balwa et al., 2016)	S1: 0.0012 S2: 0.0011 S3: 0.0014 AV: 0.001	0.005	0.001
9.	Mercury (Hg)	mg/L	0,002 (Chander et al., 2015) 0.069-0.082 (Riza et al., 2021)	S1: 0.00016 S2: 0.00011 S3: 0.00012 AV: 0.0001	0.002	0.005
10.	Lead (Pb)	mg/L	0,2310-0,2566 (Wu et al., 2019)	S1: 0.005 S2: 0.006 S3: 0.005 AV: 0.0053	0.1	1
11.	Stannum (Sn)	mg/L	0.15 (Kazuyuki et al., 2016)	S1: 0.022 S2: 0.018 S3: 0.024 AV: 0.0213	2	3
12.	Arsenic (As)	mg/L	2,6 – 50 (Herdianita & Priadi, 2008)	S1: 0.00012 S2: 0.00011 S3: 0.00014 AV: 0.0001	0.1	0.5
13.	Selenium (Se)	mg/L	1.000 (DEGA, 2019)	S1: 0.00011 S2: 0.00012 S3: 0.00013 AV: 0.0001	0.05	0.5
14.	Nickel (Ni)	mg/L	59.6 (Bamanga, 2020)	S1: 0.053 S2: 0.052 S3: 0.051 AV: 0.0520	0.2	0.5

15.	Cobalt (Co)	mg/L	0 – 0,00025 (Soleimani et al., 2017; Dinh et al., 2018)	S1: 0.111 S2: 0.116 S3: 0.114 AV: 0.1137	0.4	0.6
16.	Cyanide (Cn)	mg/L	0,0– 10 (Yan, 1992)	S1: 0.009 S2: 0.007 S3: 0.008 AV: 0.0080	0.05	0.5
17.	Fluoride (F)	mg/L	0,0019 – 0,00282 (Soleimani et al., 2017)	S1: 0.111 S2: 0.1123 S3: 0.112 AV: 0.1118	2	3

*Cited from some references. Quality Standards 1: MER (2014). Quality Standards 2: Rice & Bridgewater (2012). S = sample. AV = average.

Table 4. Statistical analysis of heavy metal content parameters in ballast water landed in Batam, Indonesia.

	Minimum	Maximum	Mean		SD	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic	Statistic	St. Error	Statistic	Std. Error
Fe	0.83	0.84	0.8333	0.00333	0.00577	0.000	1.732	1.225	0.000	0.000
Mn	0.089	0.092	0.09067	0.000882	0.00153	0.000	-0.935	1.225	0.000	0.000
Br	0.101	0.105	0.10333	0.001202	0.00209	0.000	-1.293	1.225	0.000	0.000
Cu	0.142	0.144	0.14300	0.000577	0.00100	0.000	0.000	1.225	0.000	0.000
Zn	0.311	0.322	0.31500	0.003512	0.00608	0.000	1.680	1.225	0.000	0.000
Cr	0.018	0.027	0.02200	0.002646	0.00458	0.000	0.935	1.225	0.000	0.000
T Cr	0.078	0.086	0.08200	0.002309	0.00400	0.000	0.000	1.225	0.000	0.000
Cd	0.0011	0.00014	0.001233	0.0000882	0.00015	0.000	0.935	1.225	0.000	0.000
Hg	0.00011	0.00016	0.0001300	0.0000153	0.00003	0.000	1.458	1.225	0.000	0.000
Pb	0.005	0.006	0.00533	0.000333	0.00058	0.000	1.732	1.225	0.000	0.000
Sn	0.018	0.024	0.02133	0.001764	0.00306	0.000	-0.935	1.225	0.000	0.000
As	0.00011	0.00014	0.0001233	0.0000088	0.00002	0.000	0.935	1.225	0.000	0.000
Se	0.00011	0.00013	0.0001200	0.0000057	0.00001	0.000	0.000	1.225	0.000	0.000
Ni	0.051	0.053	0.05200	0.000577	0.00100	0.000	0.000	1.225	0.000	0.000
Co	0.111	0.116	0.11367	0.001453	0.00252	0.000	-0.586	1.225	0.000	0.000
Cn	0.007	0.009	0.00800	0.000577	0.00100	0.000	0.000	1.225	0.000	0.000
F	0.111	0.112	0.11167	0.000333	0.00058	0.000	-1.732	1.225	0.000	0.000

SD= standard deviation

Heavy metal content in ballast water can be a concern due to the potential environmental impact associated with the discharge of ballast water containing elevated levels of heavy metals. Heavy metals are metallic elements with high atomic weights and densities, and they include substances like mercury, lead, cadmium, and copper. These metals can be harmful to aquatic ecosystems and may pose risks to human health (Zahra & Kalim, 2017). The ships may take on ballast water in one location and discharge it in another, potentially transferring heavy metals from one environment to another. The sources of heavy metals in ballast water can include runoff from industrial areas, port activities, and coastal waters where ships take on ballast (Samarska et al., 2020).

Industrial activities, such as mining, metal production, and manufacturing, can contribute heavy metals to nearby water bodies. Coastal waters may contain elevated levels of heavy metals due to various anthropogenic activities. The discharge of ballast water containing high concentrations of heavy metals can introduce these pollutants to new ecosystems, potentially causing harm to aquatic life. Heavy metals can accumulate in sediments and biota, leading to long-term environmental impacts (Sharifuzzaman et al., 2016).

Heavy metals can have significant impacts on marine environments, affecting both the organisms within the ecosystems and the overall health of the water bodies. Heavy metals, such as mercury, lead, cadmium, copper, and zinc, can be toxic to aquatic organisms at elevated concentrations. These metals can disrupt physiological processes, impair growth, reproduction, and development, and even cause mortality in marine life (Kahlon et al., 2018). They can disrupt the normal functioning of marine ecosystems by affecting the behavior, physiology, and reproductive capabilities of various organisms. This disruption can lead to changes in population dynamics and community structure. Heavy metals can influence nutrient cycling in marine environments. For example, metals like copper can inhibit microbial processes involved in nutrient cycling, affecting the availability of essential nutrients for marine life (Sandeep et al., 2019).

Heavy metal contamination can have economic implications for commercial fisheries. Fish and shellfish that accumulate high levels of heavy metals may pose risks to human health if consumed, leading to potential restrictions on fishing activities. The metals can persist in the environment for extended periods, especially in sediments. This persistence can contribute to long-term ecological impacts (Sharma et al., 2021). To mitigate the impacts of heavy metals on marine environments, it is crucial to monitor and regulate industrial discharges, implement proper waste management practices, and adhere to international agreements and protocols aimed at protecting marine ecosystems from pollution, such as the Marine Pollution Prevention Convention (MARPOL) and regional regulations (Bui et al., 2021). Judging from the heavy metal levels in the parameters of ballast water waste before and after electrocoagulation, the electrocoagulation treatment has reduced the levels of this waste far below the predetermined quality standard threshold. This opinion feels more convincing if we compare the heavy metal levels in untreated ballast water in column 4 of Table 3. This figure appears to be far above the heavy metal contents obtained in this study.

3.3 Other chemical and biological parameters

Other chemical parameters show that treated ballast water has met the requirements to be returned to nature (MER, 2014, Rice & Bridgewater, 2012). Acidity around 7.13, sulfide (< 0.002 mg/L), fluoride (0.11 mg/L), chlorine (0.05 mg/L), ammonia (0.78 mg/L), nitrate (< 0.05 mg/L), nitrite (< 0.004 mg/L), total nitrogen (0.78 mg/L) and BOD5 (22.69 mg/L). This figure looks very far from the initial parameters and levels before electrocoagulation was carried out. This means that electrocoagulation technology works very effectively in reducing waste levels in water ballast. This figure appears to meet the requirements for waste to be subsequently disposed of in nature. More detailed data is presented in Table 5.

Statistical analysis shows that the standard deviation of the data ranges between 0.0001732-2.646 and the variance ranges between 0.000-7.000. This shows that the data for sulfide, chlorine, ammonia, nitrate, nitrite, total nitrogen, bod5, methylene blue, phenol, oil and fat, pH, and total coliform for ballast water are relatively uniform and normally distributed. The skewness test results show that the heavy metal content data for ballast water ranges from -1.732 - 1.732 meaning that the data is distributed relatively in the middle. This is following the analysis of kurtosis values, where the values are all 0.00 or <3 (leptokurtic curve), meaning that the data is spread tending to the right and left (Table 6).

The reduction of hazardous chemical and biological in liquid waste has been reported by researchers. This liquid waste varies, from urban waste, factory waste, and detergent waste to ballast water waste. Ge et al., (2004) reported the removal of phosphate, surfactant, and turbidity from laundry wastewater by electrocoagulation system more than 90% in a wide pH range of 5-9. Phutdhawong et al., (2000) claimed a phenolic compound and other particle removal from aqueous waste by using an electrocoagulation process. Ibanez et al. (1995) and Rubach & Saur (1997) removed oily wastewater up to 60-99 % and 95-99 %, respectively. Ugurlu (2004), and Sivakumar (2005) reduced the nitrite, nitrate, and ammonia content 95 by applying batch EC. By using Al/Al monopolar floated and settled EC system Hu et al., (2005), Sivakumar & Emamjomeh (2005a), Sivakumar & Emamjomeh (2005b), Emamjomeh & Sivakumar (2005), Ma et al., (2007) and Hu et al., (2007) reported the reduction fluoride content in some liquid waste up to 99 %. Kobya et al., (2005) and Hutnan et al., (2005) reduced municipal wastewater COD by up to 93 and 80 %. Islam et al., (2011) BOD5 and COD in treated effluents some liquid waste in Bangladesh. Borchate et al., (2014) also mentioned that EC effectively reduced the organic matters which contributes to the BOD and COD content of the wastewater.

Sulfide and chlorine are chemical components that can be found in ballast water, and their presence can have implications for the environment and the effectiveness of ballast water management practices. Sulfide is a compound containing the element sulfur. In the context of ballast water, sulfides may be present naturally in some coastal waters or may be introduced through industrial discharges. High concentrations of sulfides in ballast water can be toxic to aquatic organisms. Sulfide toxicity can affect fish and othermarine life, leading to adverse impacts on the local ecosystem (Tavares-Dias. 2021).

Chlorine is commonly used as a disinfectant in ballast water treatment systems. Ships may use chlorine-based methods to control the transfer of invasive species or pathogens in ballast water. While chlorine is effective in killing or neutralizing many organisms in ballast water, its residual presence in discharged water can have environmental consequences. Chlorine can be toxic to aquatic life, and its release into the receiving waters may harm local ecosystems (Jesus et al., 2013).

Nitrogen in ballast water can exist in various forms, including nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), and organic nitrogen compounds. Nitrogen content in ballast water can be a significant environmental concern, as the discharge of ballast water containing elevated levels of nitrogen compounds may contribute to nutrient loading in receiving waters. Nitrogen is a vital nutrient for aquatic ecosystems, but excessive levels can lead to various ecological issues. Nitrogen is a crucial

Table 5. Other chemical and biological parameters of ballast water before and after electrocoagulation.

No.	Parameter	Unit	Before coagulation*	After coagulation	Quality Standards 1	Quality Standards 2
1.	Sulfide (H_2S)	mg/L	10,555-19,172 (Wu et al., 2019)	S1: 0.0021 S2: 0.0025 S3: 0.0024 AV: 0.0023	0.5	1
2.	Chlorine (Cl_2)	mg/L	0.0 (Wu et al., 2019)	S1: 0.052 S2: 0.055 S3: 0.054 AV: 0.054	1	2
3.	Ammonia (NH_3-N)	mg/L	0,016 (Guney & Yonsel, 2011)	S1: 0.782 S2: 0.781 S3: 0.790 AV: 0.784	30	60
4.	Nitrate (NO_3-N)	mg/L	0.04 (Wu et al., 2019)	S1: 0.052 S2: 0.054 S3: 0.051 AV: 0.052	50	150
5.	Nitrite (NO_2-N)	mg/L	0,049-0,101 (Wu et al., 2019)	S1: 0.0041 S2: 0.0038 S3: 0.0041 AV: 0.0040	1	3
6.	Total Nitrogen	mg/L	30 (Pung-Guk & Hyung-Gon, 2020)	S1: 0.791 S2: 0.772 S3: 0.781 AV: 0.781	30	60
7.	BOD_5	mg/L	2.0-3.6 (Wu et al., 2019)	S1: 22,712 S2: 22,681 S3: 22,688 AV: 22,693	50	150
8.	Methylene blue active compound	mg/L	5-25 (Dang et al., 2006)	S1: 0.733 S2: 0.732 S3: 0.731 AV: 0.732	5	10
9.	Phenol	mg/L	1 (Phutdhawong et al., 2000)	S1: 0.0012 S2: 0.0013 S3: 0.0012 AV: 0.0012	0.5	1
10.	Oil and fat	mg/L	15 (Rubach & Saur., 1997)	S1: 1.052 S2: 1.022 S3: 1.022 AV: 1.032	10	20
11.	pH		7,976-8,10 (Sayinli et al., 2022)	S1: 7.11 S2: 7.14 S3: 7.13 AV: 7.127	6 – 9	6 – 9
12.	Total Coliform	MPN/100ml	10^3-10^6 (Takahashi et al., 2008	S1: 617 S2: 616 S3: 612 AV: 615	10,000	10,000

*Cited from some references. Quality Standards 1: MER (2014). Quality Standards 2: Rice & Bridgewater (2012). S1 = sample 1. S2 = sample 2. S3 = sample 3. AV = average.

Table 6. Statistical analysis of meters for sulfide, chlorine, ammonia, nitrate, nitrite, total nitrogen, BOD5, methylene blue, phenol, oil and fat, pH, and total coliform levels in ballast water landed in Batam, Indonesia.

	Minim.	Maxim.	Mean		SD	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	St. Error	Statistic	Statistic	Statistic	Std. Error	Statistic	St. Error
Sulfide	0.0021	0.0025	0.0023	0.0001202	0.00021	0.000	-1.293	1.225	0.000	0.000
Clorine	0.052	0.055	0.0537	0.000882	0.00153	0.000	-0.935	1.225	0.000	0.000
Ammonia	0.781	0.790	0.7843	0.002848	0.00493	0.000	1.652	1.225	0.000	0.000
Nitrate	0.051	0.054	0.0523	0.000882	0.00152	0.000	0.935	1.225	0.000	0.000
Nitrite	0.0038	0.0041	0.0040	0.0001000	0.00017	0.000	-1.732	1.225	0.000	0.000
Total Nitrogen	0.772	0.791	0.7813	0.005487	0.00950	0.000	0.158	1.225	0.000	0.000
BOD5	22.681	22.712	22.694	0.009387	0.01626	0.000	1.378	1.225	0.000	0.000
Methylene Blue	0.731	0.733	0.7320	0.000577	0.00100	0.000	0.000	1.225	0.000	0.000
Phenol	0.0012	0.0013	0.0012	0.0000333	0.00006	0.000	1.732	1.225	0.000	0.000

SD= standard deviation

nutrient for marine life, supporting the growth of algae and other aquatic plants. However, excessive nitrogen can lead to nutrient enrichment, causing problems like eutrophication (Khan & Mohammad, 2014). Eutrophication can lead to algal blooms, oxygen depletion, and changes in the structure and function of aquatic ecosystems. Harmful algal blooms, in particular, can have detrimental effects on marine life and human health (Glibert et al., 2011). Data from previous research on acidity, sulfide, fluoride, chlorine, ammonia, nitrate, nitrite, total nitrogen and BOD5 in untreated ballast water. The figures listed are all much higher (column 4, Table 5) when compared with the results of this study. From the analysis of the chemical parameters measured (acidity, sulfide, fluoride, chlorine, ammonia, nitrate, nitrite, total nitrogen and BOD5), it is clear that electrocoagulation treatment has been able to reduce the levels of waste compounds in ballast water. The figures for this parameter are far below the minimum levels determined by the established quality standards.

In this research, the author only focused on studying ballast water waste. However, if you look at the content of hazardous materials in ballast water, there are similarities with other waste materials. Sources of waste can be urban wastewater, factory waste, detergent waste, and so on. This waste continues to be produced by many people so the quantity is greater and potentially more dangerous than ballast water waste. For this reason, EC treatment can also be used for these needs in the future.

3.4. Correlation of each parameter

The results of the correlation analysis show that in general, all parameters have a weak influence or relationship with each other, where r = <0.32. However, several parameters have a moderate influence or relationship, where the r value ranges from 0.33-0.66. The strongest correlation is only a moderate correlation (r = 0.5). For example, Mn-total coliform levels, Cu-Pb levels, NO2 and phenol, Hg-Cr, Pb-Ni and Se, and As and others. This condition is understandable considering that generally, these parameters do not influence each other in a significant way. For more details on the relationship between each parameter, see Table 7.

4. CONCLUSIONS

The physical parameters of the treated ballast water showed temperatures of 28ºC, TDS, and TSS of around 140 and 11 mg/L respectively. The main heavy metal content of ballast water after the electrocoagulation process showed the respective figures for cadmium (< 0.001 mg/L), chrome (< 0.02 mg/L), mercury (< 0.0001 mg/L), lead (< 0.005 mg/L), copper (0.14 mg/L), zinc (0.31 mg/L), and Arsenic (< 0.0001 mg/L). Acidity around 7.13, sulfide (< 0.002 mg/L), fluoride (0.11 mg/L), chlorine (0.05 mg/L), ammonia (0.78 mg/L), nitrate (< 0.05 mg/L), nitrite (< 0.004 mg/L), total nitrogen (0.78 mg/L) and BOD_5 (22.69 mg/L). All metrics demonstrated a significant reduction in the amount of electrocoagulated ballast water waste and compliance with ballast water waste quality criteria. The EC method is very effective in reducing pollutant levels. It turns out that it has also been tested to process other waste. So, it is very promising to develop this technique for other waste treatment purposes in the future.

Table 7. Correlation between parameters (physics, chemistry and biology) of ballast water landed at several ports in Batam, Indonesia.

	Temp.	TDS	TSS	Fe	Mn	Br	Cu	Zn	Cr	TCr	Cd	Hg	Pb	Sn	As	Se	Ni	Co	Cn	F	S^{2-}	Chl	NH_3	NO_3	NO_2	T N	BOD_5	MB	Phenol	O&F	pH	T C
Temp.	1.00	0.11	0.31	0.19	0.04	0.11	0.35	0.21	0.38	0.02	0.38	0.13	0.15	0.25	0.38	0.35	0.35	0.06	0.02	0.19	0.11	0.08	0.45	0.25	0.15	0.03	0.12	0.35	0.15	0.19	0.08	0.46
TDS	0.11	1.00	0.41	0.08	0.15	0.00	0.24	0.10	0.48	0.09	0.48	0.02	0.26	0.36	0.48	0.24	0.24	0.05	0.09	0.08	0.00	0.03	0.44	0.36	0.26	0.08	0.01	0.24	0.26	0.08	0.03	0.35
TSS	0.31	0.41	1.00	0.49	0.26	0.41	0.34	0.48	0.07	0.32	0.07	0.43	0.16	0.05	0.07	0.34	0.34	0.36	0.32	0.49	0.41	0.38	0.14	0.05	0.16	0.33	0.42	0.34	0.16	0.49	0.38	0.24
Fe	0.19	0.08	0.49	1.00	0.23	0.08	0.17	0.03	0.44	0.17	0.44	0.06	0.33	0.44	0.44	0.17	0.17	0.13	0.17	0.00	0.08	0.11	0.37	0.44	0.33	0.16	0.07	0.17	0.33	0.00	0.11	0.27
Mn	0.04	0.15	0.26	0.23	1.00	0.15	0.39	0.25	0.33	0.06	0.33	0.17	0.11	0.21	0.33	0.39	0.39	0.10	0.06	0.23	0.15	0.12	0.41	0.21	0.11	0.07	0.16	0.39	0.11	0.23	0.12	0.50
Br	0.11	0.00	0.41	0.08	0.15	1.00	0.24	0.10	0.48	0.09	0.48	0.02	0.26	0.36	0.48	0.24	0.24	0.05	0.09	0.08	0.00	0.03	0.44	0.36	0.26	0.08	0.01	0.24	0.26	0.08	0.03	0.35
Cu	0.35	0.24	0.34	0.17	0.39	0.24	1.00	0.14	0.27	0.33	0.27	0.23	0.50	0.39	0.27	0.00	0.00	0.30	0.33	0.17	0.24	0.27	0.20	0.39	0.50	0.32	0.24	0.00	0.50	0.17	0.27	0.11
Zn	0.21	0.10	0.48	0.03	0.25	0.10	0.14	1.00	0.41	0.19	0.41	0.09	0.36	0.47	0.41	0.14	0.14	0.16	0.19	0.03	0.10	0.13	0.34	0.47	0.36	0.18	0.10	0.14	0.36	0.03	0.13	0.25
Cr	0.38	0.48	0.07	0.44	0.33	0.48	0.27	0.41	1.00	0.39	0.00	0.50	0.23	0.12	0.00	0.27	0.27	0.43	0.39	0.44	0.48	0.45	0.07	0.12	0.23	0.40	0.49	0.27	0.23	0.44	0.45	0.17
TCr	0.02	0.09	0.32	0.17	0.06	0.09	0.33	0.19	0.39	1.00	0.39	0.11	0.17	0.27	0.39	0.33	0.33	0.04	0.00	0.17	0.09	0.06	0.47	0.27	0.17	0.01	0.10	0.33	0.17	0.17	0.06	0.44
Cd	0.38	0.48	0.07	0.44	0.33	0.48	0.27	0.41	0.00	0.39	1.00	0.50	0.23	0.12	0.00	0.27	0.27	0.43	0.39	0.44	0.48	0.45	0.07	0.12	0.23	0.40	0.49	0.27	0.23	0.44	0.45	0.17
Hg	0.13	0.02	0.43	0.06	0.17	0.02	0.23	0.09	0.50	0.11	0.50	1.00	0.27	0.38	0.50	0.23	0.23	0.07	0.11	0.06	0.02	0.05	0.43	0.38	0.27	0.10	0.01	0.23	0.27	0.06	0.05	0.33
Pb	0.15	0.26	0.16	0.33	0.11	0.26	0.50	0.36	0.23	0.17	0.23	0.27	1.00	0.11	0.23	0.50	0.50	0.20	0.17	0.33	0.26	0.23	0.30	0.11	0.00	0.18	0.26	0.50	0.00	0.33	0.23	0.39
Sn	0.25	0.36	0.05	0.44	0.21	0.36	0.39	0.47	0.12	0.27	0.12	0.38	0.11	1.00	0.12	0.39	0.39	0.31	0.27	0.44	0.36	0.33	0.20	0.00	0.11	0.28	0.37	0.39	0.11	0.44	0.33	0.29
As	0.38	0.48	0.07	0.44	0.33	0.48	0.27	0.41	0.00	0.39	0.00	0.50	0.23	0.12	1.00	0.27	0.27	0.43	0.39	0.44	0.48	0.45	0.07	0.12	0.23	0.40	0.49	0.27	0.23	0.44	0.45	0.17
Se	0.35	0.24	0.34	0.17	0.39	0.24	0.00	0.14	0.27	0.33	0.27	0.23	0.50	0.39	0.27	1.00	0.00	0.30	0.33	0.17	0.24	0.27	0.20	0.39	0.50	0.32	0.24	0.00	0.50	0.17	0.27	0.11
Ni	0.35	0.24	0.34	0.17	0.39	0.24	0.00	0.14	0.27	0.33	0.27	0.23	0.50	0.39	0.27	0.00	1.00	0.30	0.33	0.17	0.24	0.27	0.20	0.39	0.50	0.32	0.24	0.00	0.50	0.17	0.27	0.11
Co	0.06	0.05	0.36	0.13	0.10	0.05	0.30	0.16	0.43	0.04	0.43	0.07	0.20	0.31	0.43	0.30	0.30	1.00	0.04	0.13	0.05	0.02	0.50	0.31	0.20	0.03	0.06	0.30	0.20	0.13	0.02	0.40
Cn	0.02	0.09	0.32	0.17	0.06	0.09	0.33	0.19	0.39	0.00	0.39	0.11	0.17	0.27	0.39	0.33	0.33	0.04	1.00	0.17	0.09	0.06	0.47	0.27	0.17	0.01	0.10	0.33	0.17	0.17	0.06	0.44
F	0.19	0.08	0.49	0.00	0.23	0.08	0.17	0.03	0.44	0.17	0.44	0.06	0.33	0.44	0.44	0.17	0.17	0.13	0.17	1.00	0.08	0.11	0.37	0.44	0.33	0.16	0.07	0.17	0.33	0.00	0.11	0.27
S^{2-}	0.11	0.00	0.41	0.08	0.15	0.00	0.24	0.10	0.48	0.09	0.48	0.02	0.26	0.36	0.48	0.24	0.24	0.05	0.09	0.08	1.00	0.03	0.44	0.36	0.26	0.08	0.01	0.24	0.26	0.08	0.03	0.35
Chl	0.08	0.03	0.38	0.11	0.12	0.03	0.27	0.13	0.45	0.06	0.45	0.05	0.23	0.33	0.45	0.27	0.27	0.02	0.06	0.11	0.03	1.00	0.47	0.33	0.23	0.05	0.04	0.27	0.23	0.11	0.00	0.38
NH_3	0.45	0.44	0.14	0.37	0.41	0.44	0.20	0.34	0.07	0.47	0.07	0.43	0.30	0.20	0.07	0.20	0.20	0.50	0.47	0.37	0.44	0.47	1.00	0.20	0.30	0.48	0.44	0.20	0.30	0.37	0.47	0.09
NO_3	0.25	0.36	0.05	0.44	0.21	0.36	0.39	0.47	0.12	0.27	0.12	0.38	0.11	0.00	0.12	0.39	0.39	0.31	0.27	0.44	0.36	0.33	0.20	1.00	0.11	0.28	0.37	0.39	0.11	0.44	0.33	0.29
NO_2	0.15	0.26	0.16	0.33	0.11	0.26	0.50	0.36	0.23	0.17	0.23	0.27	0.00	0.11	0.23	0.50	0.50	0.20	0.17	0.33	0.26	0.23	0.30	0.11	1.00	0.18	0.26	0.50	0.00	0.33	0.23	0.39
T N	0.03	0.08	0.33	0.16	0.07	0.08	0.32	0.18	0.40	0.01	0.40	0.10	0.18	0.28	0.40	0.32	0.32	0.03	0.01	0.16	0.08	0.05	0.48	0.28	0.18	1.00	0.09	0.32	0.18	0.16	0.05	0.43
BOD_5	0.12	0.01	0.42	0.07	0.16	0.01	0.24	0.10	0.49	0.10	0.49	0.01	0.26	0.37	0.49	0.24	0.24	0.06	0.10	0.07	0.01	0.04	0.44	0.37	0.26	0.09	1.00	0.24	0.26	0.07	0.04	0.34
MB	0.35	0.24	0.34	0.17	0.39	0.24	0.00	0.14	0.27	0.33	0.27	0.23	0.50	0.39	0.27	0.00	0.00	0.30	0.33	0.17	0.24	0.27	0.20	0.39	0.50	0.32	0.24	1.00	0.50	0.17	0.27	0.11
Phenol	0.15	0.26	0.16	0.33	0.11	0.26	0.50	0.36	0.23	0.17	0.23	0.27	0.00	0.11	0.23	0.50	0.50	0.20	0.17	0.33	0.26	0.23	0.30	0.11	0.00	0.18	0.26	0.50	1.00	0.33	0.23	0.39
O&F	0.19	0.08	0.49	0.00	0.23	0.08	0.17	0.03	0.44	0.17	0.44	0.06	0.33	0.44	0.44	0.17	0.17	0.13	0.17	0.00	0.08	0.11	0.37	0.44	0.33	0.16	0.07	0.17	0.33	1.00	0.11	0.27
pH	0.08	0.03	0.38	0.11	0.12	0.03	0.27	0.13	0.45	0.06	0.45	0.05	0.23	0.33	0.45	0.27	0.27	0.02	0.06	0.11	0.03	0.00	0.47	0.33	0.23	0.05	0.04	0.27	0.23	0.11	1.00	0.38
TC	0.46	0.35	0.24	0.27	0.50	0.35	0.11	0.25	0.17	0.44	0.17	0.33	0.39	0.29	0.17	0.11	0.11	0.40	0.44	0.27	0.35	0.38	0.09	0.29	0.39	0.43	0.34	0.11	0.39	0.27	0.38	1.00

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