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Modeling of *E. coli* Inactivation from Solutions using GInaFiT via Hybrid Electrode Connected Electro-Disinfection Process

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Abstract: *E. coli* (*Escherichia coli*) is a bacterium found in human and animal intestines. These bacteria, which can enter the bloodstream through as anyway as the environment or food, can cause many diseases such as diarrhea, respiratory problems, and blood/urinary tract infections, especially in humans. Therefore, these bacteria have to be removed from drinking water sources by some inactivation methods. Conventional methods such as chlorination, ozonation, and UV inactivation methods are effective. But the development of techniques that do not require the transportation and storage of chemicals and do not produce negative by-products and are cost-effective on the basis of environmental engineering studies. In this study, the inactivation effectiveness of a hybrid electrode-connected electrochemical process as a new approach on *E. coli* was investigated. The connection system was experienced with Al/SS/SS as Anode/Cathode/Anode electrode. Simultaneously electrocoagulation (EC) and electrooxidation (EO) mechanism works together in this electrode connection system. The inactivation coefficients were determined by the GInaFiT (Geeraerd and Van Impe Inactivation Model Fitting Tool) modeling tool, which is a Microsoft Excel add-on and the model was statistically well fitted with Double-Weibull. 4D degradation of *E. coli* was achieved as 21 minutes at a current density of 0.3 A and an optical density (O.D.) of 0.21. It has been determined that hybrid electrode-connected electro-disinfection process is an effective approach for the *E. coli* inactivation.

Keywords: Electro-disinfection, *E. coli*, inactivation models, hybrid electrode, Double Weibull.

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1. INTRODUCTION

One of the most basic needs for people and all other living things to continue their vital activities is clean drinking and utility water. For this reason, clean water supply, water treatment, and water recovery will be the most important research topics for all countries today and in the future.

Drinking and using water must comply with the minimum standards determined by each country. Physical, chemical, organic, inorganic and bacteriological parameters are used in the evaluation of water quality. Total coliform and fecal coliform parameters are generally used in the evaluation of bacteriological contamination in water. One of the markers of bacteriological contamination in waters as a pathogenic microorganism is *E. coli* (Escherichia coli), a Gram (-) member of the Enterobacteriaceae family. *E. coli* is a subgroup of fecal coliform. A general distribution diagram of bacteriological indicators and *E. coli* in water is shown in Figure 1. (W.S. Dep. of Health Division of Env. Health Office of Drinking Water).

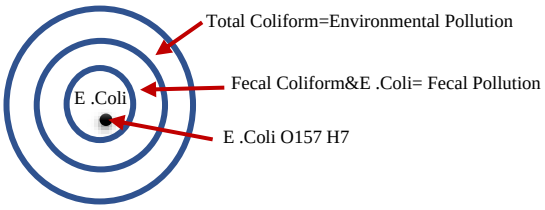


Figure 1. General distribution chart of *E. coli*

The usage of electrochemical processes has increased in recent years due to the convenience of operating/investment costs, ease of operation and alternative treatment processes to conventional processes. Electrochemical processes can simultaneously remove many pollutants such as chemical oxygen demand (COD) (Solak et al., 2023 a and b), suspended solid (SS), color, and heavy metals. To remove pathogenic microorganisms, chemical processes such as Cl_2 (Fiorentino et al., 2021), O_3 (Taoran Liu et al., 2019), physical processes such as ultraviolet (UV) (Fiorentino et al., 2021) or their hybrid configurations and advanced filtration techniques such as membrane filtration processes (Saleh et al., 2021) are used.

Electrochemical processes, which have recently been used and developed as environmentally friendly, are accepted as promising methods for pathogen removal from water (Feng et al., 2004; Delaedt et al., 2008; Li et al., 2011). Electrochemical technologies include disinfection types such as electrosorption (Matsunaga et al., 2000), and electrophoresis (Rowan et al., 2001). In addition, electrochemical processes have been successfully applied in the inactivation of different organisms (bacteria, viruses and microalgae) (Li et al., 2011). Bacterial inactivation of *E. coli* and Legionellapneumophila occurs effectively in various studies where electrochemical processes are applied. (Delaedt et al., 2008; Feng et al., 2004; Diao et al., 2004; Liv et al., 2004; Patermarakis and Fountoukidis 1990). *E. coli* is effectively removed by the EC process, which is one of the electrochemical processes. The most commonly used electrode types in these processes are Aluminum (Al) and Iron (Fe) electrodes as they are cheap and easy to supply (Haydar and Aziz, 2009; Mohammed and Sivakumar, 2009; Holt et al., 2005). The EO process is a subsection of electrochemical processes in which insoluble electrodes such as TiO_2, Ti/RuO_2, SS, and BBD are generally used. This process is effective for the degradation of organic pollutants (Diaz et al., 2011) and bacteriological pathogens (Isidro et al., 2020).

To determine the mechanism and the efficacy of the inactivation processes some predictive models are used. These models are also grouped as primary, secondary, and tertiary models. Primary models track a microorganism's reaction to a single set of circumstances throughout time. The response might be either direct or indirect indicators of microbial population density or metabolic products. Secondary models define how primary model parameters vary in response to one or more environmental or cultural elements (for example, atmosphere, pH, temperature, etc.). Tertiary models are computer-based adaptations of primary and secondary models (Whiting and Buchanan, 1993). In the study, a tertiary model was preferred to model the *E. coli* inactivation of the hybrid electrode-connected electro-disinfection process with the GInaFiT modeling program, which is a Microsoft Excel add-on.

Real-life applications show that there is no single treatment method that can perform a complete, efficient and cost-effective disinfection process in accordance with the literature. The aim of the study is to develop a new approach to the hybrid electrode connected electro disinfection process, to determine the effective applied current, to determine the inactivation capability of pathogenic microorganisms and to determine which model fits the *E. coli* inactivation with hybrid electrochemical technique.

2. MATERIAL and METHOD

2.1. Preparation of *E. coli* suspension

In the study, the water that was electrochemically disinfected was prepared synthetically with sterile water. *E. coli* (ATCC 25922) was prepared from lyophilized strains as specified by the ATCC. The resulting biomass was used to create cellular suspensions at appropriate bacterial densities in sterile electrolytic solutions. 3N NaCl (Merck) was used to provide electrochemical conductivity, and 0.1 N HCl and 0.1 N NaOH were used to neutralize water.

2.2. Electro-disinfection Experimental Studies

A water-cooled reactor with a volume of 0.5 L, made of plexiglass, was used in the removal of *E. coli* from wastewater employing electro-disinfection process. The reactor internal dimensions were 8x8x11cm. 0.45 L water was used in each experiment. Anode/Aluminum (Al)/(+), Cathode/Stainless Steel (SS)/(-), Anode/Stainless Steel (SS)/(+) electrodes with approximately 80 cm^2 active surface area were used in the electro-disinfection process. (Figure 2). Electrode dimensions were 10cmx4cm; The dimensions that react in water were 5cmx4cm.

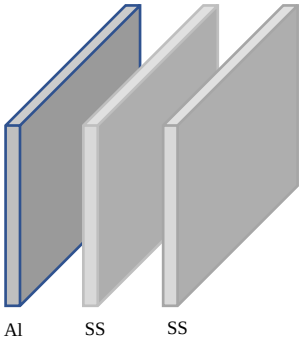


Figure 2. Hybrid connection of electrodes

The experimental design is given in Figure 3. The reaction was started after the electrodes, which were prepared synthetically and whose absorbance at 600 nm was determined, were washed with HCl on the wastewater surfaces of which the number of colonies was determined, and placed in the reactor. During the reaction, the sample was mixed with a magnetic stirrer at 300 rpm. The temperature, which was measured continuously during the reaction, was

kept at room temperature by the water-cooling system outside the reactor. In the first stage, the variation of *E. coli* inactivation with time was observed at constant *E. coli* and current densities. The effect of the current on constant *E. coli* concentration was determined.

The opacity of a bacterial solution which is called optical density (OD600) of the *E. coli* was analyzed by using a Hach DR6000 spectrophotometer at a 600 nm wavelength. The initial and residual number of *E. coli* in the wastewater was determined by counting.

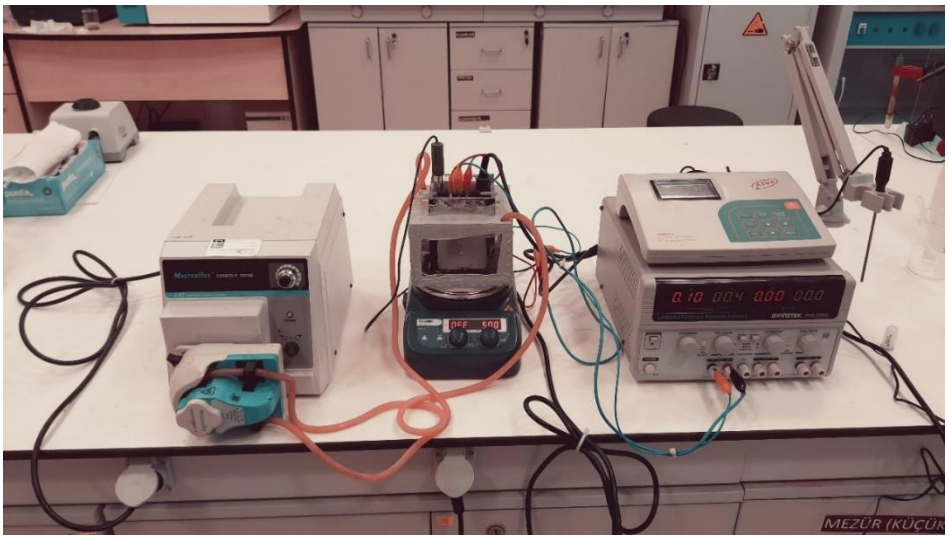


Figure 3. Experimental set-up of electro-disinfection

2.3. Determination of Inactivation Coefficient

Inactivation curves corresponding to the experimental data were performed using the Microsoft Excel add-in tool GInaFiT, developed by Geeraerd (Geeraerd ve Van Impe Inactivation Fitting Tool). With GInaFiT, the change of bacterial cells (log CFU/ml) damaged by disinfection methods over time is determined by various microbial inactivation models. Models used: Log-linear, Log-linear + shoulder, Log-linear + tail, Log-linear + shoulder + tail, Weibull, Weibull + tail, Double Weibull, Biphasic Model and Biphasic + shoulder. In addition, model parameters such as the inactivation coefficient in the GInaFiT program provide information on various subjects such as the resistance of bacterial cells to stress, residual cell concentration and purification efficiency. Inactivation models' equations and coefficients are given in Table 1.

Table 1. Inactivation models' equations and coefficients

Model	Equations	Coefficients	Reference
Log-linear	$N = N_0.\exp(-k_{max}.t)$	k_{max}	Bigelow and Esty 1920
Log-linear shoulder	$N = N_0.\exp(-k.t).(\exp(k.SI))/(1+(\exp(k.SI)-1).\exp(-k.t)))$	k, SI	Geeraerd et al., 2000
Log-linear tail	$N = (N_0 - N_{res}).\exp(-k.t) + N_{res}$	k, N_{res}	Geeraerd et al., 2000
Log-linear shoulder+tail	$N = (N_0 - N_{res}).\exp(-k.t).((\exp(k.SI)))/(1+(\exp(k.SI) - 1.\exp(-k.t))) + N_{res}$	k, N_{res}, SI	Geeraerd et al., 2000
Weibull	$N/N_0 = 10^{(-\left(\left(\frac{t}{a}\right)^n\right))}$	a, n	Mafart et al.,2002.
Weibull fixed p	$N/N_0 = 10^{(-\left(\left(\frac{t}{\delta}\right)^p\right))}$	p	Mafart et al.,2002.
Weibull+tail	$N = (N_0 - N_{res}).10^{\left(-\left(\left(\frac{t}{a}\right)^n\right)\right)} + N_{res}$	a, n, N_{res}	Albert and Mafart 2005.
Double Weibull	$N(t) = \left(\frac{N_0}{(1+10^{\alpha})}\right).\left((10^{-\left(\frac{t}{a_1}\right)^{n_1+\alpha}} + 10^{-\left(\frac{t}{a_2}\right)^{n_2}}\right)$	a_1, a_2, n_1, n_2, a	Coroller et al. 2006.
Biphasic	$N = N_0.(f.\exp(-k_1.t) + (1-f.\exp(-k_2.t))$	f, k_1, k_2	Cerf et al, 1977.
Biphasic + shoulder	$log_{10}(N) = log_{10}(N_0) + \frac{log_{10}(f.\exp(-k_1.t).\exp(k_1.SI))}{1+(\exp(k_1.SI)-1).\exp(-k_1.t)}.\left(1 - f.exp(-k_2.t).\frac{\exp(k_2.SI)}{1+(\exp(k_1.SI)} - 1\right).\exp(-k_1.t))\text{^}(k_2/k_1))$	f, k_2, k_2, SI	Geeraerd et al., 2006.

N: microbial population at any time; N_0: initial microbial population; k: specific inactivation coefficient; N_{res}: residual population density; Sl: shoulder length; a: scale parameter; n: shape parameter; k_1 and k_2: specific inactivation rates of the two subpopulations; f: fraction of the initial population in a less resistant subpopulation.

2.4. Equations

In microbial inactivation studies, logarithmic removal efficiency is calculated by Equation 1.

$$log\,removal = -log_{10}(N_0/N_t) \qquad \textbf{Eq. 1}$$

N_0= initial concentration of *E. coli* (CFU/mL), N_T= *E. coli* concentration at time t (CFU/mL)

The current density was calculated by Equation 2.

$$J = I/A \qquad \textbf{Eq. 2.}$$

Here; J: Current density, A/m^2, I: current (Ampere), A: Active surface area, cm^2.

3. RESULTS and DISCUSSION

3.1. Experimental Results

0.1 A (1.25 mA/cm^2), 0.2 A (2.5 mA/cm^2 and 0.3 A (3.75 mA/cm^2) current was applied to the Al/SS/SS connected electrochemical process. The experimental results of the study are given in Table 2. Initial number of *E. coli* was varied from 54.10^6 to 56.10^6. When 0.1 A current was applied to the water, 4D degradation of *E. coli* was achieved in >30 minutes, and in a 0.2 A was applied current >38 minutes. In a 0.3 A applied current, 4D was achieved at a minute of 21. The inactivation effectiveness of the process was increased with the increase of applied current.

Table 2. Experimental results

	0.1 A (1.25 mA/cm^2)			**0.2 A (2.5 mA/cm^2)**			**0.3 A (3.75 mA/cm^2)**		
Time (min.)	***E. coli* Number**	**Log N/No**	**R.E. (%)**	***E. coli* Number**	**Log N/No**	**R.E. (%)**	***E. coli* Number**	**Log N/No**	**R.E. (%)**
0	54000000	0	0	56000000	0	0	56000000	0	0
2	52000000	-0.01639	3.703704	38000000	-0.1684	32.14286	54000000	-0.01579	3.571429
4	50000000	-0.03342	7.407407	31000000	-0.25683	44.64286	48000000	-0.06695	14.28571
6	48000000	-0.05115	11.11111	29000000	-0.28579	48.21429	14900000	-0.575	73.39286
8	47000000	-0.0603	12.96296	12500000	-0.65128	77.67857	12700000	-0.64438	77.32143
10	32500000	-0,22051	39.81481	10000000	-0.74819	82.14286	5400000	-1.01579	90.35714
12	32300000	-0.22319	40.18519	5100000	-1.04062	90.89286	4000000	-1.14613	92.85714
14	19800000	-0.43573	63.33333	4200000	-1.12494	92.5	3600000	-1.19189	93.57143
16	11300000	-0.67932	79.07407	4000000	-1.14613	92.85714	1400000	-1.60206	97.5
18	11100000	-0.68707	79.44444	3500000	-1.20412	93.75	1340000	-1.62108	97.60714
20	8600000	-0.7979	84.07407	2400000	-1.36798	95.71429	1190000	-2.5	97.875
22	8400000	-0.80811	84.44444	1700000	-1.51774	96.96429	190	-5.46943	99.99966
24	7500000	-0.85733	86.11111	1250000	-165128	97.76786			
26	6300000	-0.93305	88.33333	220000	-2.40577	99.60714			
28	5900000	-0.96154	89.07407	50000	-3.04922	99.91071			
30	1480000	-1.56213	97.25926	28000	-3.30103	99.95			
32	1340000	-1.60529	97.51852	0		100			
34	1210000	-1.64961	97.75926						
36	1190000	-1.65685	97.7963						
38	230000	-2.3067	99.57407						
40	30000	-3.25527	99.94444						

3.2. Optical Density of the *E. coli* Colony

0.1 A (1.25 mA/cm^2), 0.2 A (2.5 mA/cm^2 and 0.3 A (3.75 mA/cm^2) current was applied to the Al/SS/SS connected electrochemical process. The absorbance values (Optical Density600-OD600) are given in Table 3. The density of a cell suspension (Optical Density) is related to the number of cells, and optical density is employed to assess this density. With the use of this measurement, it will be possible to estimate how the decrease in *E. coli* cells has affected the media's opacity. (Kourdali et al., 2018).

Table 3. The optical density of *E. coli*

	Applied Current		
	0.1 A (1.25 mA/cm^2)	**0.2 A (2.5 mA/cm^2)**	**0.3 A (3.75 mA/cm^2)**
Time (min.)	**Abs (600nm)**	**Abs (600nm)**	**Abs (600nm)**
0	0.512	0.530	0.530
2	0.510	0.523	0.514
4	0.504	0.512	0.509
6	0.503	0.489	0.494
8	0.501	0.481	0.472
10	0.496	0.439	0.429
12	0.492	0.381	0.332
14	0.489	0.369	0.325
16	0.484	0.352	0.283
18	0.473	0.351	0.258
20	0.444	0.300	0.200
22	0.434	0.248	0.145
24	0.377	0.168	
26	0.346	0.142	
28	0.300	0.134	
30	0.287	0.092	
32	0.239	0.085	
34	0.228		
36	0.207		
38	0.146		
40	0.111		

OD_{600} values for different applied current values are given in Figure 4. As it is seen in Figure 4 that OD_{600} values of *E. coli* inactivation were almost the same for all applied current values at a time of 0 to 8 min. After 8 min. inactivation effect of 0.1 A current was less effective than 0.2 A and 0.3 A. 4D inactivation of *E. coli* was determined at a time of 21 min. The increase of current increases the *E. coli* inactivation. It is thought that applying a 0.4 A current can present a shorter time 4D inactivation opportunity.

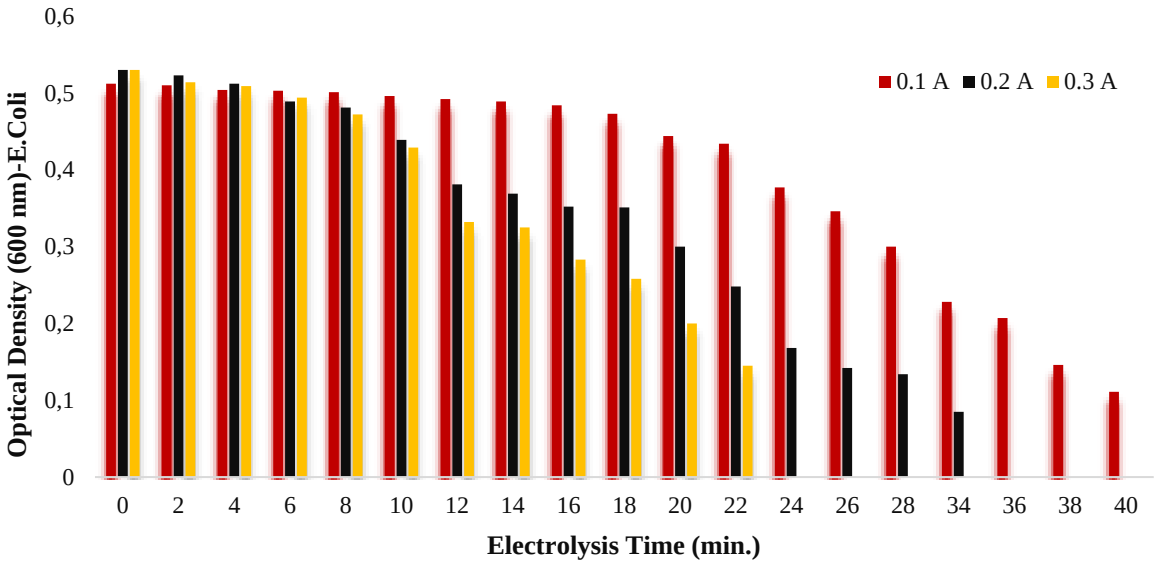


Figure 4. OD 600 Values for 0.1 A, 0.2 A and 0.3 A

Outlet **c**oncentration of *t* versus electrolysis time is given in Figure 5.

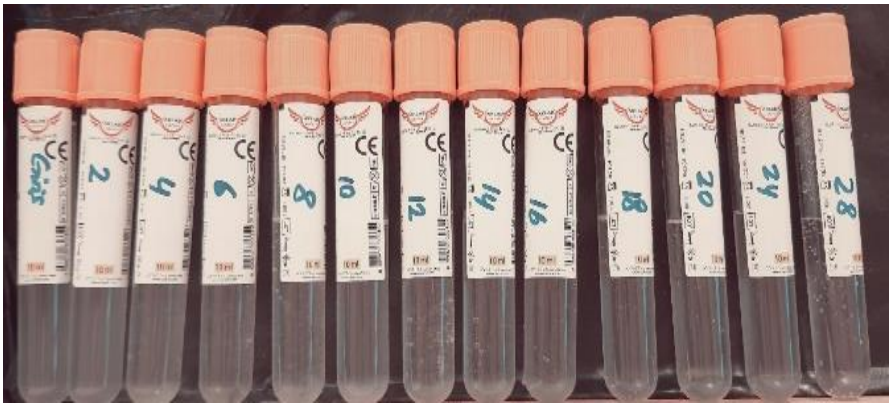


Figure 5. Outlet Concentration of *E. coli* versus electrolysis time (for 0.3 A)

3.3. Data Modeling of *E. coli* Inactivation Kinetics

The GInaFit was used to determine the inactivation model of the electro-disinfection process. GInaFit is an add-in Excel component (https://cit.kuleuven.be/biotec) that was released by Geeraerd et al. (2015). This programme can be applied by selecting the time versus log N/N_0. Then the GInafit plugin is selected (Figure 6) and the desired model is created with the help of the plugin (Figure 7). With this plugin, statistical parameters such as coefficient of determination (R^2), adjusted R^2, sum of squares of error (SSE), sum of squares of mean error (MSE), root mean square error (RMSE), experimental and estimated values, and 2D graphs can be obtained (Figure 8). The significance of the models and parameters is evaluated by these statistical parameters.

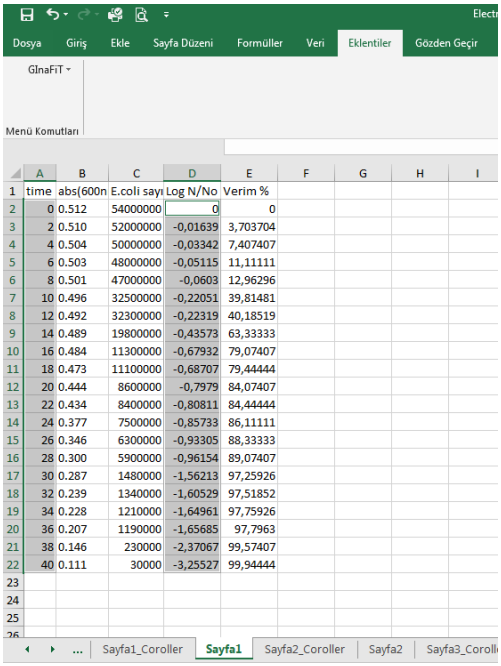


Figure 6. Selecting the time versus log N/N_0

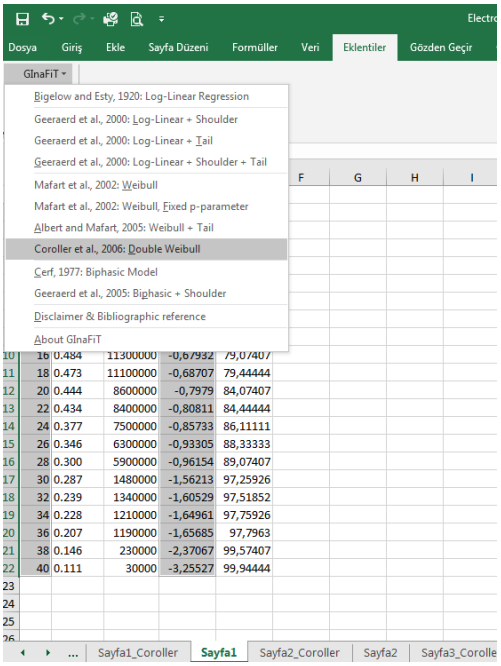


Figure 7. Selecting the model

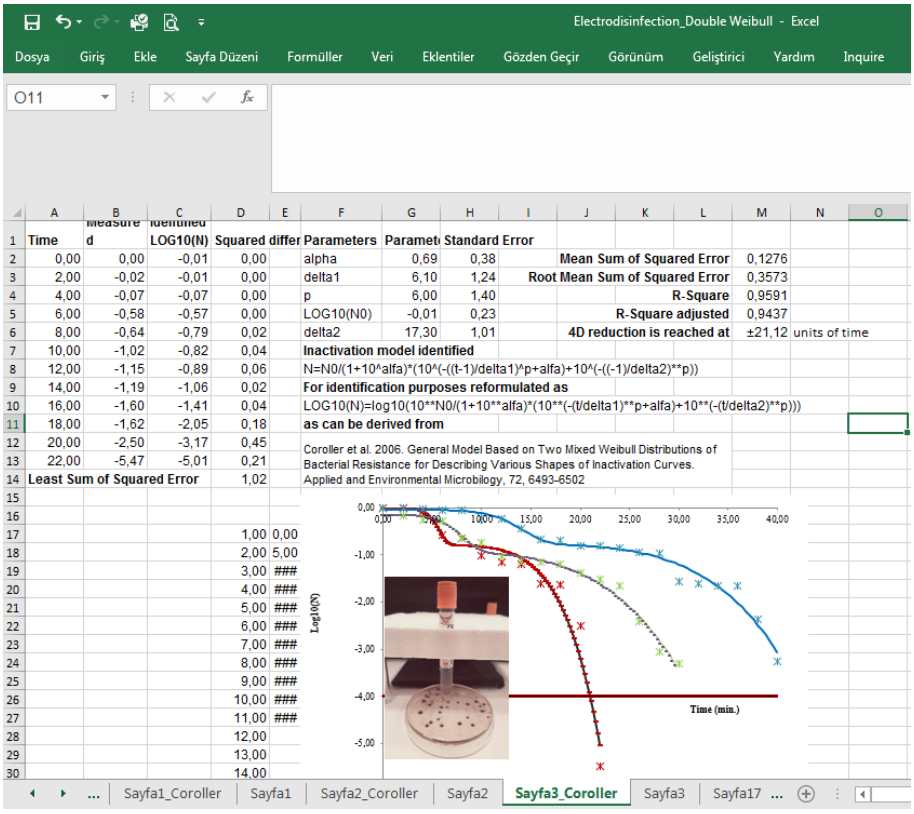


Figure 8. Evaluation of model results of the GInaFit

Modeling kinetic parameters of *E. coli* under different current densities is given in Table 4.

Table 4. Inactivation models and coefficients

Model	**Current (A)**	**R^2**	**R^2_{adj}**	**a**	**b**	**kmax**	**c**	**$Log_{10}(N_0)$**	**c**				
Log-linear	0.1	0.86	0.85	0.1116	0.3341	0.15	0.01	0.39	0.14				
	0.2	0.90	0.89	0.1025	0.3201	0.22	0.02	0.22	0.15				
	0.3	0.71	0.68	0.7354	0.8576	0.40	0.08	0.61	0.47				
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**kmax**	**c**	**$Log_{10}(N_0)$**	**c**	**Sl**	**c**	**4D reduction is reached at**	
Log-linear shoulder	0.1	0.92	0.91	0.0681	0.2611	0.24	0.03	-0.10	0.11	16.65	2.65		
	0.2	0.93	0.92	0.0814	0.2852	0.30	0.04	-0.21	0.16	9.18	2.66		
	0.3	0.87	0.84	0.3721	0.6100	2.36	0.60	-0.71	0.20	17.65	0.85	21.56	
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**kmax**	**c**	**$Log_{10}(N_0)$**	**c**	**$Log_{10}(N_{res})$**	**c**		
Log-linear tail	0.1	0.86	0.84	0.1178	0.3433	0.15	0.02	0.39	0.17	-13.35	$> 70.10^6$		
	0.2	0.90	0.88	0.1103	0.3322	0.22	0.03	0.22	0.18	-15.03	$> 10.10^{11}$		
	0.3	0.82	0.90	0.7052	0.6397	0.40	0.12	0.61	0.54	-14.75	$> 41.10^{10}$		
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**kmax**	**c**	**$Log_{10}(N_0)$**	**c**	**$Log_{10}(N_{res})$**	**c**	**Sl**	**c**
Shoulder tail	0.1	0.92	0.90	0.0722	0.2686	0.24	0.06	-0.10	0.12	-33.89		16.65	3.26
	0.2	0.93	0.91	0.0881	0.2969	0.30	0.07	-0.21	0.18	-33.42		9.18	3.33
	0.3	0.87	0.82	0.4186	0.6470	2.36	1.33	-0.71	0.22	-17.56	$> 44.10^{11}$	17.65	1.13
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**delta**	**c**	**$Log_{10}(N_0)$**	**c**	**p**	**c**	**4D reduction is reached at**	
Weibull	0.1	0.94	0.93	0.0493	0.2221	27.08	1.52	-0.11	0.09	2.48	0.35		
	0.2	0.95	0.94	0.0573	0.2394	17.91	1.53	-0.26	0.12	2.06	0.33		
	0.3	0.89	0.86	0.3192	0.5650	15.88	1.24	-0.53	0.23	4.89	1.21	±21.12	
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**delta**	**c**	**$Log_{10}(N_0)$**	**c**	**p**	**c**		
Weibull fixed	0.1	0.91	0.89	0.1076	0.3280	10.49	3.09	0.20	0.26	1.02	0.24		
	0.2	0.86	0.85	0.1151	0.3393	15.89	4.55	0.37	0.24	1.02	0.26		
	0.3	0.71	0.64	0.8064	0.8980	5.85	4.71	0.59	0.76	1.02	0.55		

	Current (A)	R^2	R^2_{adj}	a	b	delta	c	$Log_{10}(N_0)$	c	p	c	$Log_{10}(N_{res})$	c		
Weibull tail	0.1	0.94	0.93	0.0522	0.2285	27.08	1.60	-0.11	0.10	2.48	0.56	-12.23	16.10^8		
	0.2	0.95	0.94	0.0621	0.2492	17.91	1.70	-0.26	0.14	2.06	0.51	-13.38	95.10^8		
	0.3	0.92	0.89	0.2577	0.5077	17.41	1.16	6.60	3.15	-0.54	0..20	-15.48	36.10^9		
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**Alpha**	**c**	**Delta 1**	**c**	**P**	**c**	**$Log_{10}(N_0)$**	**c**	**Delta 2**	**c**
Double Weibull	0.1	0.98	0.98	0.14	0.019	0.70	0.14	8.97	0.9	4.22	0.59	-0.14	0.08	24.11	0.84
	0.2	0.97	0.97	0.15	0.022	0.61	0.13	15.34	1.14	5.7	0.84	-0.04	0.07	34.52	0.83
	0.3	0.96	0.94	0.36	0.13	0.69	0.38	6.1	1.24	6	1.4	0.01	0.23	17.30	1.01
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**f**	**c**	**$Log_{10}(N_0)$**	**c**	**kmax1**	**c**	**kmax2**	**c**		
Biphasic	0.1	0.86	0.83	0.1248	0.3532	0.8475	90.10^{13}	0.39	0.15	0.15	-	0.15	-		
	0.2	0.90	0.88	0.1195	0.3457	0.8722		0.22	-	0.22	-	0.22	-		
	0.3	0.71	0.60	0.9192	0.9588	0.7763	19.10^{14}	0.61	0.54	0.40	-	0.40	-		
	Current (A)	**R^2**	**R^2_{adj}**	**a**	**b**	**f**	**c**	**$Log_{10}(N_0)$**	**c**	**kmax1**	**c**	**kmax2**	**c**	**Sl**	
Biphasic shoulder	0.1	0.92	0.90	0.0767	0.2769	1.0000	-	-0.10	-	0.24	-	0.24	-	16.65	
	0.2	0.93	0.90	0.0962	0.3101	1.0000	-	-0.21	-	0.30	-	0.30	-	9.18	
	0.3	0.87	0.79	0.4784	0.6917	1.0000	-	-0.71	-	2.36	-	2.36	-	17.65	

c: Standart Error

A log-linear equation, which is based on the idea that there is a negative and linear relationship between cell count and deadly treatment/inactivation rate, is the most fundamental method for describing the inactivation kinetics (Bevilacqua et al., 2015). R^2, and adjusted R^2 were checked to determine the adequacy of the models. The R^2 value of the Log-linear model for 0.1 A, 0.2 A and 0.3 A was determined as 0.86, 0.9 and 0.71, respectively, while R^2adj values were 0.85, 0.89 and 0.68, respectively. The 2D plot of the Log-linear inactivation model is given in Figure 9a. The term "log-linear shoulder model" describes first-order inactivation kinetics that have the shoulder parameter added (Geeraerd et al. 2000). R^2 values of the Log-linear shoulder model for 0.1 A, 0.2 A and 0.3 A were determined as 0.92, 0.93 and 0.87, respectively, while R^2_{adj} values were 0.91, 0.92 and 0.84, respectively. Figure 9b shows the log-linear shoulder inactivation model of *E. coli*. Log-linear tail model refers to conventional first-order inactivation kinetics with an added tail parameter (Geeraerd et al. 2000). R^2 values of the Log-linear tail model for 0.1 A, 0.2 A and 0.3 A were determined as 0.86, 0.90 and 0.82, respectively, while R^2_{adj} values were 0.84, 0.88 and 0.90, respectively. But the minimum value that may be measured is less than Log10(N_{res}). For this data, a model with tailing is implausible, and the findings do not fit the model. Log-linear shoulder tail model refers to conventional first-order inactivation kinetics with an added shoulder and tail parameter (Geeraerd et al. 2000). R^2 values of Log linear shoulder tail model for 0.1 A, 0.2 A and 0.3 A were determined as 0.92, 0.93 and 0.87, respectively, while R^2_{adj} values were 0.90, 0.91 and 0.82, respectively. Log10 (N_{res}), however, is lower than the smallest measured value. For this data, a model with tailing is implausible, and the findings do not fit the model.

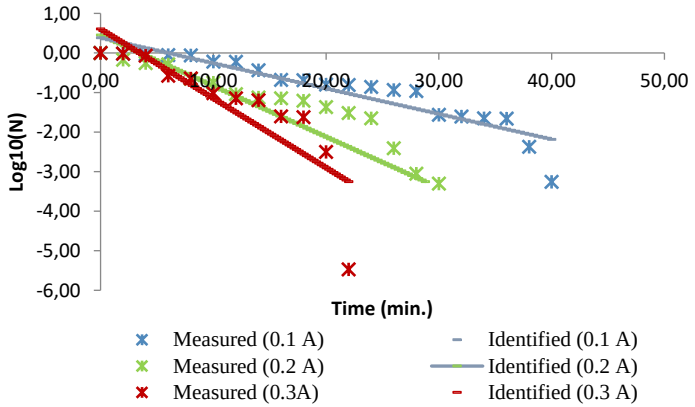
The Biphasic model assumes an initially large subpopulation that is more susceptible to stress (smoother steady decline) and a smaller subpopulation that is more resistant to stress (smoother steady decline) (Cerf et al., 1977). R^2 values of Biphasic model for 0.1 A, 0.2 A and 0.3 A were determined as 0.86, 0.90 and 0.71, respectively, while R^2_{adj} values were 0.83, 0.88 and 0.60, respectively. However, the parameter estimate for k_{max1} equals k_{max2} perfectly. This shows that the biphasic model is unlikely to fit the facts in this case. R^2 values of the Biphasic shoulder model for 0.1 A, 0.2 A and 0.3 A were determined as 0.92, 0.93 and 0.87, respectively, while R^2_{adj} values were 0.90, 0.90 and 0.79, respectively. The parameter estimates for k_{max1} and k_{max2} are identical. This shows that the biphasic model is unlikely to fit the facts in this case.

R^2 values of the Weibull model for 0.1 A, 0.2 A and 0.3 A were determined as 0.94, 0.95 and 0.89, respectively, while R^2_{adj} values were 0.93, 0.94 and 0.86, respectively. Figure 9c presents the Weibull inactivation model. R^2 values of Weibull fixed p model for 0.1 A, 0.2 A and 0.3 A were determined as 0.91, 0.86 and 0.71, respectively, while R^2_{adj} values were 0.89, 0.85 and 0.64, respectively. The 2D plot of the Weibull fixed p model is given in Figure 9d. R^2 values of the Weibull tail model for 0.1 A, 0.2 A and 0.3 A were determined as 0.94, 0.95 and 0.92, respectively, while R^2_{adj} values were 0.93, 0.94 and 0.89, respectively. But, the minimum value that may be measured is less than Log10(Nres). For this data, a model with tailing is unlikely for these data. The Double Weibull model assumes that in the first wave, there is a large subpopulation more sensitive to stress, while in the second wave, there is a small subpopulation that is more resistant to stress (Coroller et al., 2006). R^2 values of the Double Weibull model for 0.1 A, 0.2 A and 0.3 A were determined as 0.98, 0.97 and 0.96, respectively, while R^2_{adj} values were 0.98, 0.97 and 0.94, respectively. Figure 9e shows the Double Weibull inactivation model. The Double Weibull model had a high signal, which is thought to explain the electro-disinfection process for *E. coli* inactivation.

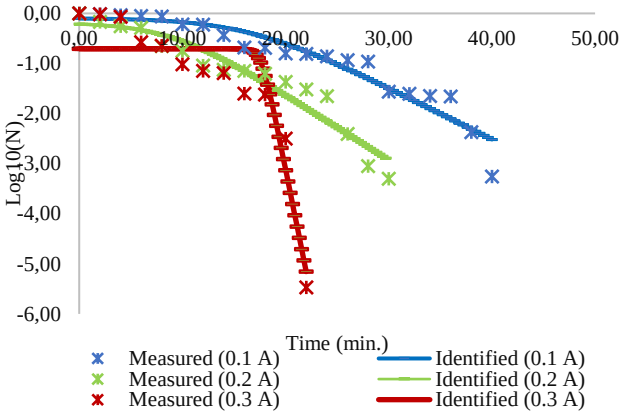
2D Plots of inactivation models are given in Table 2. The mean square error (RMSE) and coefficient of determination (R^2) parameters were used to evaluate the fit of the model. Finally, with the mathematical kinetic models in GInaFit, the model that will explain the hybrid electrode-connected electro-disinfection process and the *E. coli* removal model was chosen. It was observed that the inactivation curves obtained in the study fit with the Double Weibull model. In order to determine the effective current value, the time required for the microbial population to decrease by 4 log (t4D) was determined together with the Double Weibull model. This model was built on the assumption that the population is comprised into two subpopulations with varying stress resistances, and that the inactivation kinetics of both subpopulations follow a Weibull distribution (Coroller et al., 2006). In a study, Double Weibull model was obtained for the *E. coli* inactivation as present study (Hwang et al., 2019).

In the study, a hybrid electrode system was used. In this system, both EC process and EO processes work together. Accordingly, the mechanisms of both electrochemical methods are effective in the reactor. It has been reported that *E. coli* inactivation by electrochemical disinfection process using Pt as anode electrode occurs by two different mechanisms including direct oxidation on the electrode surface and indirect oxidation due to hydroxyl radicals (Jeong et al., 2007). Inactivation by EC process has both direct and indirect effects. Electric field application produces a direct effect. The indirect impact, on the other hand, is caused by microorganisms coming into contact with oxidants produced by water electrolysis and anode dissolution (Drogui et al., 2001; Li et al., 2004, Drees et al., 2003; Ghernaout et al., 2008). All these considerations lead to the hypothesis that the use of a hybrid electrode coupling system should be highly effective in *E. coli* inactivation. In the study, it was observed that *E. coli* inactivation was realized effectively.

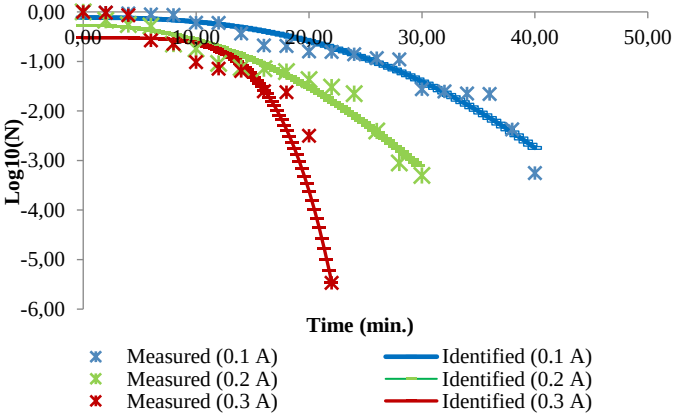
Table 2 D Plots of Inactivation Models



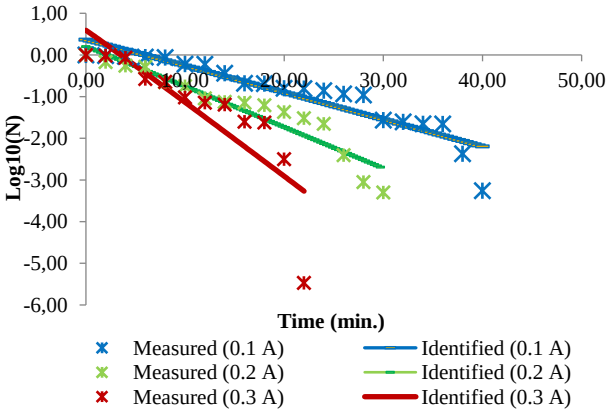
a) Log linear



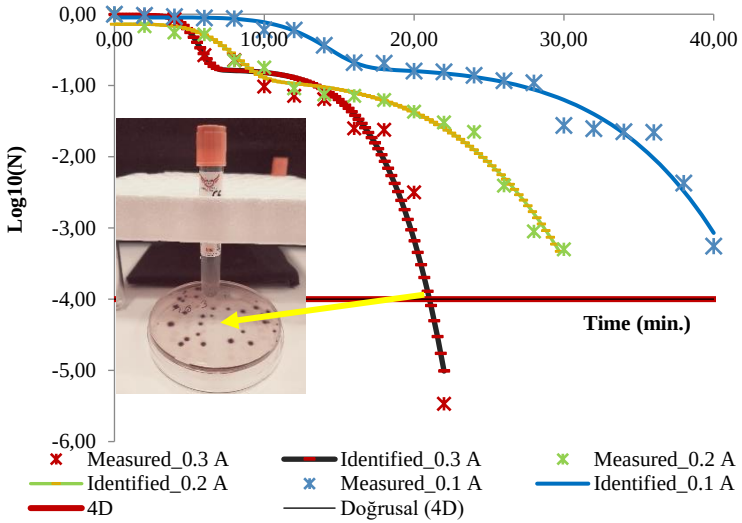
b) Log linear shoulder



c) Weibull



d) Weibull fix p



*** Log linear tail**
*** Log linear shoulder+tail**
*** Weibull+tail**

**** Biphasic**
**** Biphasic + shoulder**

* Log10(Nres) is less than the minimal measured value. Model with tailing is unlikely for these data.

** The parameter estimate for kmax1 is exactly equal to kmax2. This indicates that the biphasic model is unlikely for these data.

e) Double Weibull

Figure 9. 2D Plots of Inactivation models

4.CONCLUSION

E. coli is a parameter that should be evaluated bacteriologically, especially for drinking water. Since it is a pathogenic microorganism, its removal from drinking water is very important. In this study, the inactivation efficiency of *E. coli* with the electro-disinfection process using a hybrid electrode connection system, which is a new approach, and the inactivation kinetics of *E. coli* were determined. The increase in applied current also shows its significant efficiency in terms of *E. coli* cell inactivation and disintegration (OD_{600}). At an applied current of 0.1 A and 0.2 A, 4D inactivation of *E. coli* could not be reached. At an applied current of 0.3 A, 4D degradation of *E. coli* was occurred at an electrolysis time of 21.12 min. It has been determined that the inactivation model was compatible with the Double Weibull model. As a result, a hybrid electrode connected electro-disinfection process could be a reliable approach and a significant alternative to conventional methods for *E. coli* inactivation from water/wastewater.

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N/A

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Conflict of Interest
The authors have no conflicts of interest to declare.

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