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Analysis of the Phytoremediation Dynamic System of Lead in Mangrove Plants at the Wonorejo River Estuary, Surabaya, Indonesia

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ABSTRACT

Lead (Pb) is a non-essential heavy metal found as an inorganic pollutant in the water, sediment, and mangrove plant tissue in Wonorejo River Estuary. Several studies showed that its concentration exceeds the quality standard stipulated in the Indonesian Government Regulation Number 22 of 2021 and the EPA sediment quality. Moreover, the phytoremediation of Pb through mangroves *Avicennia alba, Rhizophora stylosa, Sonneratia caseolaris,* and *Avicennia marina* at Wonorejo River Estuary was investigated. It was discovered that the environmental factors such as temperature, pH, and salinity as well as bioconcentration factor (BCF) and translocation factor (TF) values are different for each species. The dynamics of the Pb phytoremediation system were also modeled using Vensim PLE x64 software to determine the effect of environmental factors such as temperature, pH, salinity, BOD and COD, as well as Pb concentration on the ability of mangroves to accumulate and translocate Pb. The results showed that a behavioral mechanism pattern was formed based on the relationship between the environmental factors, Pb concentration, and the phytoremediation ability of the mangroves with time. This pattern affected the root and leaf BCF values of each mangrove. Furthermore, the validation test showed that the model is structurally valid and has MAPE values for the Pb phytoremediation model with *S. caseolaris* and *R. stylosa* having <30% while *Avicennia marina* and *A. alba* had <50%. Therefore, the model was categorized as fairly good with a valid forecast. The system dynamics predicted that the highest concentrations of Pb in water, roots, and stems in 2041 were in *R. stylose* at 1,329,110 mg/L, 2,054,110 mg/kg, and 3,393,950 mg/kg, respectively. The highest accumulation value in plant tissue was dominated by mangrove species of *R. stylose*. In conclusion, the environmental parameter values at habitat of *R. stylose* were in good condition for the growth of the mangroves compared with other species of mangrove.

Keywords: dynamic system, lead accumulation, environmental factors, Wonorejo River Mangroves, Vensim PLE.

INTRODUCTION

Surabaya City is located in the eastern part of Java Island and an area drained by several rivers. The utilization of river water resources for different activities by the citizens indicates the need to preserve water resources in order to ensure adequate management of water quality and pollution control (Diliarosta, 2017). One of the rivers flowing through the city is the Wonorejo River which empties into the East Surabaya coast. This estuary has narrow waters, borders the Madura Strait, and is a canal of the Jagir River that carries industrial waste in its flow. It has some inorganic pollutants in the form of lead (Pb) heavy metal which are found in the water, sediment, and mangrove plants

(Febriana, 2017; Rachmawati et al, 2018; Lufthansa, 2021). The sediments such as fine silt and a blackish deep layer observed at low tide indicate the sediment accumulation process in the area (Harnani, 2009; Mulyadi et al, 2009; BLH Surabaya, 2012). Pb can be found in nature through natural and artificial processes. It is naturally present at 1–10 mg/L in surface waters such as lakes and rivers and 1–60 mg/L in underground waters (Sudarmaji et al, 2006). The presence of Pb in nature is through artificial processes such as the use of fossil fuels, batteries, metal products, gasoline, paints, pipe soldering, mining, and manufacturing activities (Martin and Griswold, 2009; Zainal and Diani, 2009). The contents from factories and motor vehicle exhausts crystallize in the air with the assistance of rainwater and later flow into water bodies (Fadillah et al, 2017). Pb concentration is also influenced by the high level of human activities, specifically those related to agriculture, waste disposal, waste accumulation, and fertilizer use, which leads to the infiltration of leachates into groundwater aquifers (Chen et al, 2016).

In environmental media, Pb decomposes over a long period without a change in its toxicity (Brass and Strauss 1981). The solubility level is quite low, hence, the Pb content in water is relatively small, both in the dissolved and suspended forms. The Pb heavy metal entering the water undergoes ion decomposition and forms complex compounds with particles in the water before being deposited at the bottom (Sutamihardja, 2006). The Wonorejo River estuary is a muddy beach and has a mangrove ecosystem with a thickness of 15–20 meters inland. The plants serve as passive samples to transfer substances from the surrounding environment and this means they are pollutants (Irawanto and Mangkoediharjo, 2015). Therefore, phytoremediation is usually applied as a water treatment technology that involves using plant species with a high population, biomass, and significant tolerance for pollutants (Napaldet and Bout, 2019).

The analysis conducted on Jagir River by PT Jasa Tirta I in 2010–2020 showed an average Pb concentration of 0.0044 mg/L while the environmental factors include pH at 6.94–7.31, the water temperature at 29.1–30.3°C, biochemical oxygen demand (BOD) at 3.55–6.36 mg/L, and chemical oxygen demand (COD) at 16.16–26.89 mg/L. Another study on Wonorejo Mine point by the East Java Provincial Environment Agency in 2018–2020 indicated an average Pb concentration of <0.0547 mg/L, pH of 7.6, the water temperature of 29.2–31°C, BOD of 5.8–10.3 mg/L, and COD of 14–22.7 mg/L. It was also discovered that the environmental factors at the Wonorejo River estuary from 2017 to 2021 include pH at 7.4–8.1, the water temperature at 28–32°C, BOD at 5.8–19 mg/L, and average Pb concentration at 0.0002 mg/L. The comparison of the BOD value in the estuary area with Wonorejo Mine and Jagir River indicates the area has a higher concentration or accumulation of organic matter.

The environmental factor values in the habitats of the four mangrove species were also observed to be different each year. This was confirmed by Wahwakhi (2015), Nastiti (2016), Febriana (2017), Rachmawati et al. (2018), and Lufthansa et al. (2021) that the average values in the Wonorejo mangrove habitat include a water pH of 7.5, sediment pH of 4.7, the water temperature of 30.2°C, sediment temperature of 28.4°C, the salinity of 29.8‰, BOD of 18.7 mg/L, and COD of 70.5 mg/L. The changes in the temperature, pH, and salinity as well as BOD and COD in each species are directly proportional to the changes in the Pb concentration in the water and sediment of the growing media. This is in line with the findings of Darmono (2001) that the concentration of heavy metals in environmental media affects soil acidity, organic matter, temperature, texture, clay minerals, concentrations of other elements, and pH. Therefore, the average Pb concentration in *A. alba, S. caseolaris, R. stylosaa,* and *A. marina* habitats was 0.99 mg/L, 1.9 mg/L, 1.3 mg/L, and 4.36 mg/L, respectively.

The three mechanisms usually used by plants to absorb and accumulate heavy metals include root uptake, translocation from roots to stems and leaves, and localization in cells and tissues (Hardiani, 2009). It has been discovered that the growth of mangroves can be influenced by the environmental factors of habitat which are very dynamic and fluctuating. Moreover, the interaction between the biotic and abiotic components has a significant effect on the stability of the ecosystem (Poedjirahajoe, 2019) and also affects the growth of mangroves and their ability as heavy metal bio-accumulators.

It was discovered that there are no previous studies conducted to determine the causal relationship between the factors mostly influencing the ability of these mangrove species to remediate heavy metal Pb in the Wonorejo River Estuary. Therefore, this study aims to determine the dynamic system in the Pb phytoremediation process of mangrove plants at this estuary in terms of the species and environmental factors. The process involved analyzing five environmental factors related to the phytoremediation process such as pH, temperature, salinity, BOD, and COD. Moreover, the modeling was performed using Vensim Personal Learning Edition (PLE) x64 software which has a simple and flexible way of building a simulation model as well as the ability to explore the behavior of the model in order to meet the objectives of this study (Alamalik, 2004).

MATERIALS AND METHODS

Study location

The study location was the Wonorejo River Estuary at coordinates 07°18’2.41”- 07°18’43.1” South Latitude and 112°44’28.49”–112°50’19.6” East Longitude which is part of the Wonorejo Mangrove Forest Ecotourism area. The river empties into the Madura Strait which serves as its northern, eastern, and southern boundaries while it is bounded on the west by the Jagir River flow. The study location is presented in Figure 1 while the coordinates of the sampling points are indicated in Table 1.

Data collection and inventory of environmental factor values

Water quality data were obtained from studies regularly conducted by relevant agencies and previous studies on the ability of mangrove plants in the Wonorejo River to accumulate Pb heavy metal as indicated in Table 1. Moreover, the environmental factors of the river and the habitats of the four mangrove species were also inventoried.

Calculation of the average Pb concentration

Calculation of the average Pb concentration values in river water, water and sediment of the mangrove habitats were conducte, as well as the mangrove plant tissues including the roots, stems, and leaves.

Calculation of the bioconcentration factor (BCF) and translocation factor (TF) values

Calculation of the bioconcentration factor (BCF) and translocation factor (TF) values to determine the ability of the four mangrove species to accumulate and translocate Pb heavy metal were conducted using equation. The equation used to calculate the BCF value is as follows:

$$BCF = \frac{[Heavy\ metal\ in\ roots]}{[Heavy\ metal\ in\ media]} \quad (1)$$

The plants with bioconcentration and translocation factor values of >1 were categorized as bio-accumulators (Usman, 2013). The bioconcentration value >1 indicates that the plants can accumulate pollutants in high concentrations in the roots or leaves while >2 is considered high (Mellem et al, 2012). The equation used to calculate the TF value is as follows:

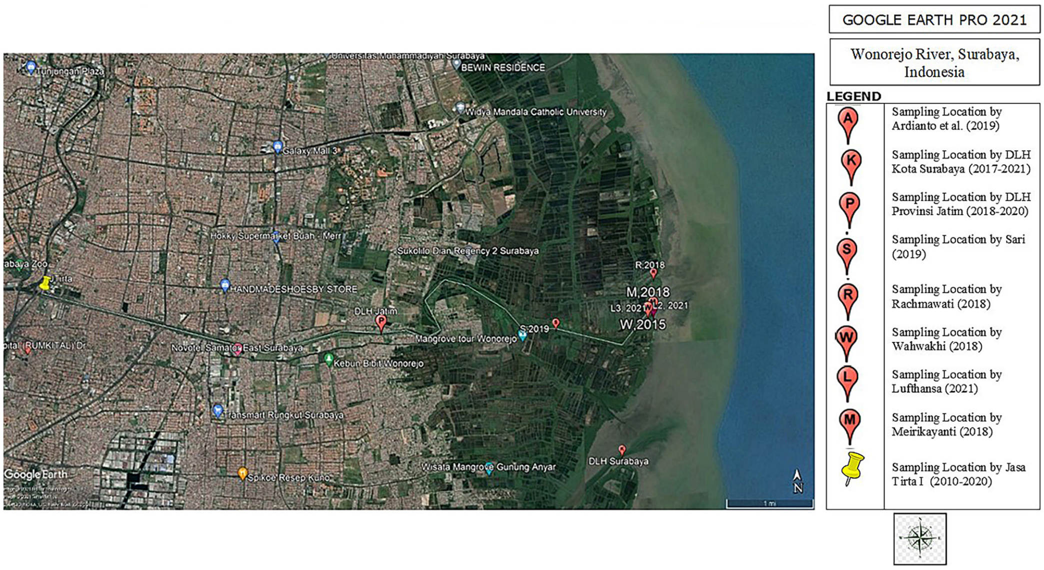


Figure 1. Map of sampling location (water, sediment and mangrove)

Table 1. Coordinates of sampling locations (water, sediment, and mangrove)

References	Sample	Plot of sampling	Coordinate	
			SL	EL
Ardianto dkk, 2019	Water	A	7°18'19,67 "	112°50'40,05"
DLH Kota Surabaya (2017-2021)	Water	K	7°19'43,1"	112°50'19,6"
DLH Provinsi Jawa Timur (2018-2020)	Water	P	7°18'29,6"	112°47'54,8"
Sari, 2019	Water, sediment, mangrove	S	7°18'28,82"	112°49'41,04"
Rachmawati dkk, 2018	Sediment, mangrove	R	7°18,07'20,57"	112°50'15,01"
Wahwakhi, 2015	Water, sediment, mangrove	W	7°18'22,78"	112°50'37,09"
Lufthansa, 2021	Water, sediment, mangrove	L	7°18'21,7"	112°50'40,6"
Meirikayanti dkk, 2018	Water	M	7°18'19,78"	112°50'40,35"
Jasa Titra I	Water	-	7°18'2,41"	112°44'28,49"

$$TF = \frac{[Heavy\ metal\ in\ stems]}{[Heavy\ metal\ in\ roots]} \quad (2)$$

The plants with bioconcentration and translocation factors of >1 and <1 as well as <1 and >1, respectively, were used as phytostabilizers and phytoextractors (Sopyan et al, 2014). According to Majid et al. (2014), the TF value has two categories, namely > 1 and < 1 classified as phytoextraction and phytostabilization, respectively.

Dynamic system

A dynamic system was used to analyze the changes in the behavior of each mangrove species in accumulating heavy metals from environmental media to plant organs over time. The stages used in analyzing the phytoremediation dynamic system of heavy metals by mangrove plants are as follows:

1. Designing causal loop diagram (CLD) to describe the causal relationship between the components of the phytoremediation model
2. Quantitative analysis using stock and flow diagram (SFD)
3. CLD and SFD were produced using dynamic system software such as Vensim PLE X64. It is important to note that the SFD was developed based on CLD (Navabi et al. (2016).
4. Formulating mathematical formulas to explain the relationship between the components of the model
5. Inputting the data into the model and model simulation
6. The model simulation was used to predict values for the planned modeling time span in the form of graphs and tables.
7. Model validation and sensitivity test

A structural validation test was conducted by providing extreme values for each equation used because the model structure is considered strong when it makes sense after extreme values are inputted. Meanwhile, the behavioral validation test indicates the model has the same behavior as the real condition when it has the same statistical output character as the output in real conditions (Forrester and Senge (1980), Richardson and Pugh (1981)). It was discovered that the simulation results were not exactly the same as the available data and this led to the application of the Mean Absolute Percentage Error (MAPE) value based on the following equation:

$$MAPE = abs\frac{(Empiric - simulation)}{Simulation} \times 100 \quad (3)$$

where: *abs* = absolute

The similarity between the simulation results and the real conditions with the same input data indicates the model was feasible to be used. Moreover, the sensitivity test was conducted on the exogenous variables in an independent and controlled system to determine the factors majorly influencing the changes in the system.

RESULTS AND DISCUSSION

Environmental factors influencing the phytoremediation of Pb heavy metal by Wonorejo mangroves

The average values of the environmental factors in the habitat based on previous studies are shown in the Table 2.

Table 2. Average values of environmental factors in the Wonorejo mangrove habitat

Mangrove spesies	Parameter						
	pH		Temperature (°C)		Salinity (‰)	BOD (mg/L)	COD (mg/L)
	Water	Sediment	Water	Sediment			
Avicennia alba	7.4	5.2	32.8	28.6	25.7	16.2	61.1
Sonneratia caseolaris	7.5	4.9	29	28.4	31.9	18.4	70.8
Rhizophora stylosa	7.5	4.0	29	28	34	13.6	50
Avicennia marina	7.7	4.5	30	28.6	27.7	26.6	100

Source: Wahwakhi (2015), Nastiti (2016), Febriana (2017), Rachmawati et al. (2018), Lufthansa et al. (2021).

The average values of Pb concentration in the water and sediment of the Wonorejo mangrove habitat

The average values of Pb concentration in water and sediment are summarized in Table 3. The quality standard for Pb concentration in water stipulated in Indonesian Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management is 0.03 mg/L, while the sediment quality standard specified in the EPA Sediment Quality is 0.04 - >0.06 mg/kg. The data in Table 3 showed that the Pb concentration in water and sediment in the habitats of the four mangroves studied exceeds the maximum concentration set out in the regulations mentioned.

The average values of Pb concentration in the Wonorejo mangrove plant tissue

The Pb heavy metal accumulated by the mangrove plants was indicated by the concentration in the tissues as shown in Table 4. The four mangrove species studied have a similarity such that the Pb concentration values in their roots are higher than in the stems and leaves. Moreover, the accumulation ability of each species was determined by calculating the Bioconcentration and Translocation Factor values.

Calculation of bioconcentration and translocation factor values

The results obtained are indicated in the following Table 5. The results showed that root BCF > 1 and leaf BCF < 1 were found in *A. alba* and *A. marina*. This means the two species have the ability to accumulate high concentrations of pollutants from the environmental media to the roots and moderately to the leaves (MacFarlane, 2007). It was also discovered that *S. caseolaris* has BCF > 2 in the root and BCF = 2 in the leaf. Mellem et al. (2012) indicated that a bioconcentration value > 2 is considered high. The findings further showed that *R. stylosa* has root BCF and leaf BCF < 1, indicating a moderate ability to accumulate pollutants from environmental media to the roots and low ability in the leaves. Meanwhile, the ability of the four mangrove species to translocate heavy metals from roots to shoots is categorized as moderate (Titah et al., 2021). It was also observed from the classification made by Sopyan et al (2014) that *A. alba*, *A. marina*, and *S. caseolaris* can be used as phytostabilizers for Pb heavy metals because they have BCF > 1 and TF < 1.

Analysis based on dynamic system

The dynamic system was used to determine the behavioral pattern of each component influencing the phytoremediation process of Pb heavy metal by the Wonorejo mangrove plants over time. The simulation time was 20 years which is from 2022 to 2041. Moreover, CLD was designed based on the relationship between the components of the planned Pb phytoremediation system, and the results produced using the Vensim software are presented in Figure 2. It was discovered from the figure that the components have a causal relationship in the Pb phytoremediation system by mangroves. This was indicated by the influence of the sediment and environmental factors such as BOD, COD, pH, salinity, and temperature on Pb solubility. Moreover, the Pb solubility and river Pb affect the water Pb concentration, while the river Pb is affected by the input Pb. The findings also showed that the extraction process was influenced by the extraction rate and fraction, and this subsequently had an impact on the sediment Pb concentration. This is indicated by

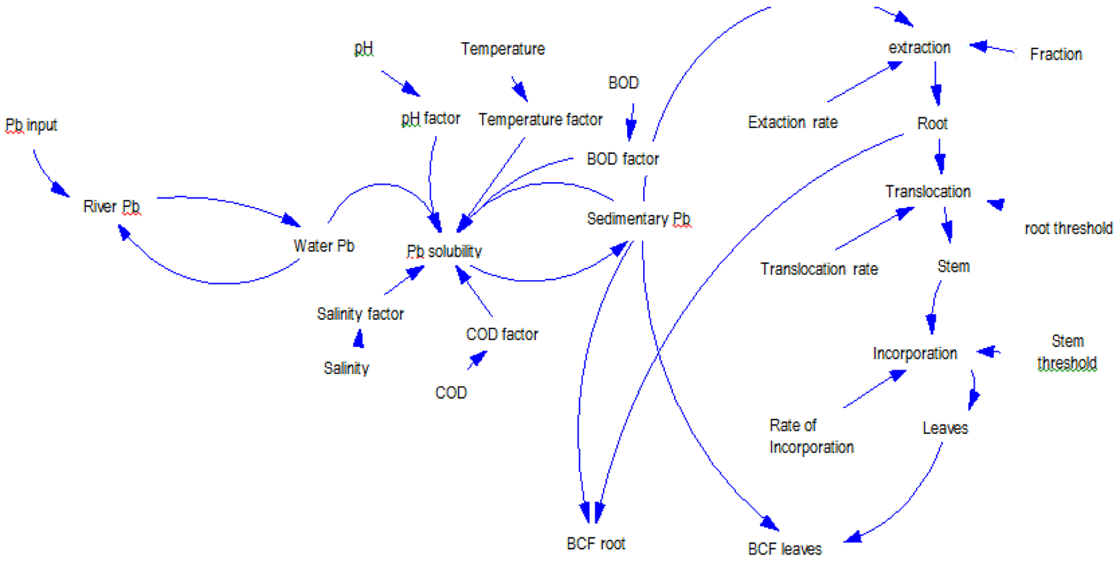


Figure 2. CLD of Pb phytoremediation system by Wonorejo mangroves

Table 3. Pb concentration in water and sediment of Wonorejo River mangrove habitat

Mangrove species	Pb in water (mg/L)	Pb in sediment (mg/kg)
Avicennia alba	0.99	15.7
Sonneratia caseolaris	1.9	0.67
Rhizophora stylosa	1.3	9.7
Avicennia marina	4.36	8.97

Source: The East Java Provincial Environment Agency (2018–2020), Surabaya City Environment Agency, (2017–2021), Wahwakhi (2015), Lufthansa et al. (2021).

the fact that the high extraction process reduced the sediment Pb concentration and this was further affected by environmental factors such as the BOD, COD, pH, salinity, and temperature. It was also observed that the reduction in the solubility of Pb in water led to an increment in its concentration in the sediment. The sediment Pb concentration was further observed in the content present in the roots and leaves after the extraction process. It is important to note that the ability of mangrove plants to extract and translocate Pb was

Table 4. Average values of Pb concentration in Wonorejo mangrove plant tissue

Mangrove species	Pb (mg/kg)		
	Roots	Stems	Leaves
Avicennia alba	21.9	3.4	8.8
Sonneratia caseolaris	1.8	0.9	1.4
Rhizophora stylosa	8.7	3	0.1
Avicennia marina	22.97	2.4	5.48

Source: Wahwakhi (2015), Nastiti (2016), Rachmawati et al (2018), Sari (2019), and Lufthansa (2021).

Table 5. Bioconcentration and translocation factor values in Wonorejo mangroves

Mangrove species	Concentration of Pb							
	Water (mg/L)	Sediment	Roots	Stems	Leaves	BCF		TF
		(mg/kg)				Roots	Leaves	
Avicennia alba	0.99	15.7	21.9	3.4	8.8	1.4	0.6	0.4
Sonneratia caseolaris	1.9	0.67	1.8	0.9	1.4	2.7	2	0.8
Rhizophora stylosa	1.3	9.7	8.7	3	0.1	0.9	0.01	0.1
Avicennia marina	4.36	8.97	22.97	2.4	5.48	2.6	0.6	0.2

determined using the BCF of the roots and leaves. The results also showed that the sediment Pb was influenced by the concentration and solubility of the heavy metal in water. Moreover, the relationship between the factors depicted in the CLD was later used to produce SFD and the components were determined in the form of Stock, Rate, and Variable as indicated in Figure 3. The data inputted in the SFD of each species were used to produce a graph showing the behavioral pattern formed in the model through the following simulation processes:

Simulation of *Sonneratia caseolaris*

The accumulation in the roots, stems, and leaves tends to be constant but later increased toward the completion of the simulation with the roots having higher accumulation compared to the leaves. This was confirmed in the BCF line which was observed to be increasing until the end of the simulation period. According to Annie and Sigua (2013), mangroves have immunity to the toxic effects of heavy metals affecting their biological and ecological processes. It is also important to note that the absorption of ions by plants was associated with two properties which include the concentration factor and quantitative differences in the nutrient requirements. Tavakkoli et al. (2010) stated that the highest concentration of ions in plant cells is found in roots. The metals are further transferred to different parts to be localized or accumulated in certain tissues. Meanwhile, Yoon et al. (2006) reported that there is a system of stopping the transportation of metal ions to the leaves from the mangrove roots, specifically in relation to the non-essential heavy metals.

Simulation *of Rhizophora stylose*

The pattern of Pb accumulation and translocation in *R. stylose* is presented in Figure 4b and it was discovered there was no significant difference between the model and the real conditions for the stems, leaves, and roots. The highest accumulation was recorded in the roots which increased at the end of the modeling period followed by the stems but the trend in the leaves was different as indicated by a decrease towards the end. Moreover, the roots were able to localize (extracellular) toxic compounds due to their inherent high level of tolerance compared to other plant parts (Dewi, 2004). It has been previously stated that plant tissues located farther away from the roots usually have smaller water potential (Feliana, 2016). This explains the reason for the increase in the accumulation of Pb which was dominated by the roots, followed by the stems, and then the leaves at the end of the modeling period.

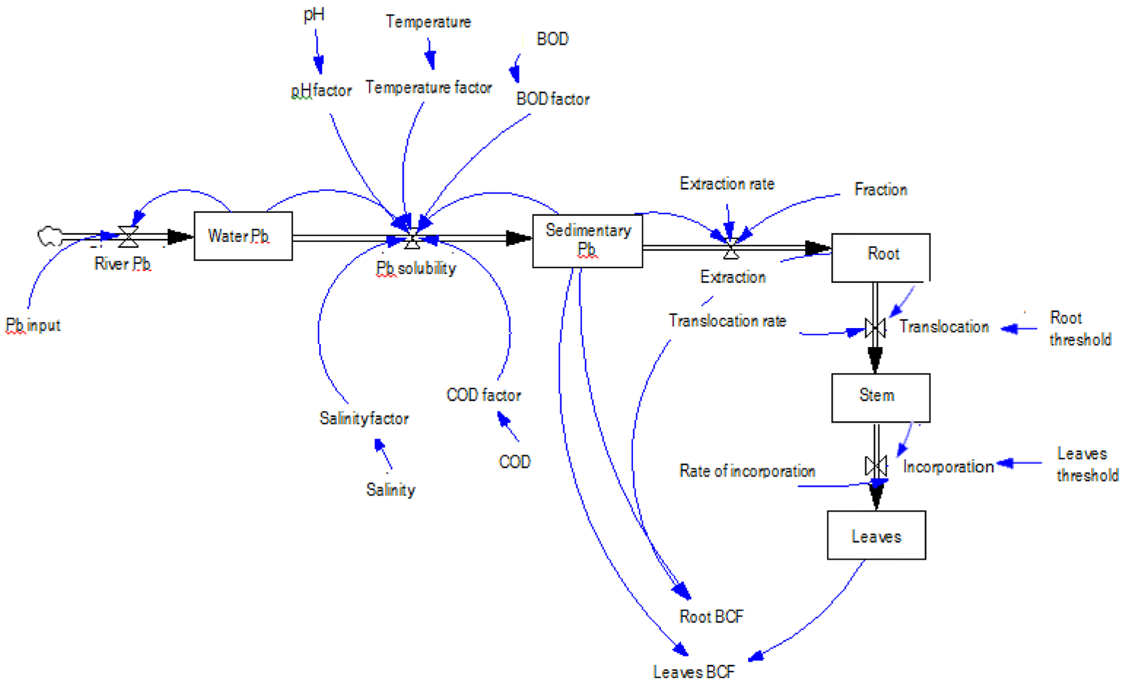


Figure 3. SFD of Pb phytoremediation system by Wonorejo mangroves

Simulation of *Avicennia alba*

The simulation results for the Pb phytoremediation dynamic system for *A. alba* are shown in Figure 4c. The change in time was observed to have increased metal accumulation in the roots and stems of *A. alba* while the leaves experience a decrease. This is similar to the pattern reported by Wahwakhi (2015) and Lufthansa (2021) which showed that the roots accumulated the highest Pb in Wonorejo *A. alba*. It was further confirmed with the accumulation ranging from 12.9–34.1 mg/kg recorded for the roots and 6.6–13.3 mg/kg for the leaves. It is important to state that *A. alba* has the same type of root as *S. caseolaris* which is known as the peg root. This type is usually located in the sediment and appears on the surface of the water, thereby making it possible to interact with Pb concentrated in air, water, and sediment media. Its attempt to transfer toxic materials into the mangrove body is indicated by the high concentration of heavy metals in the roots (Handayani, 2006).

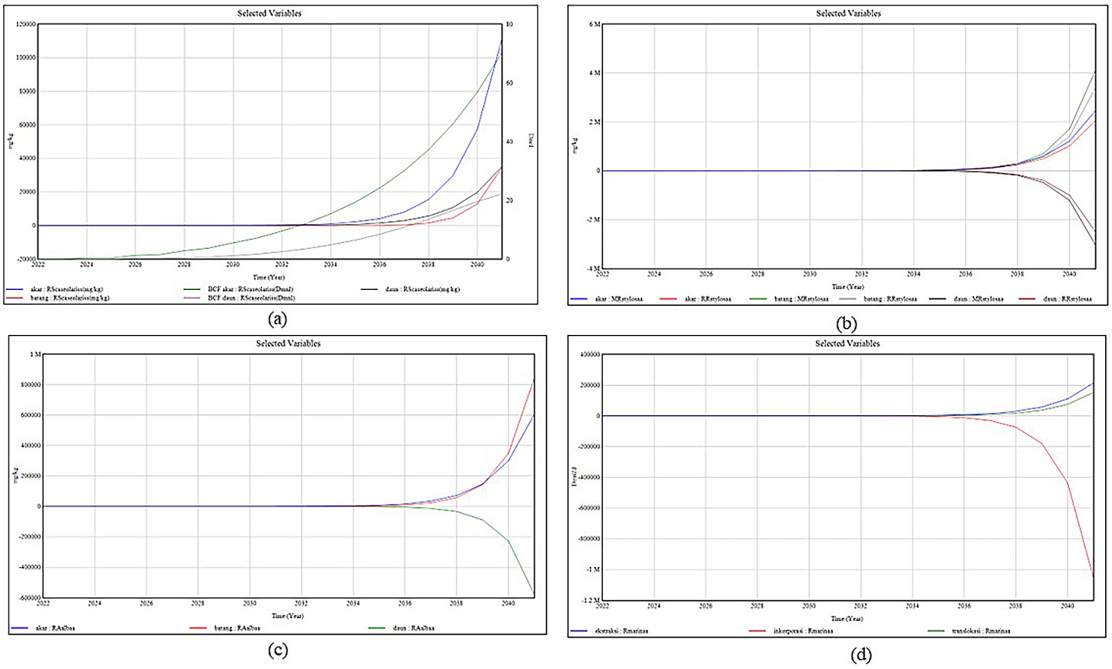
Simulation of *Avicennia marina*

The pattern obtained from simulating the root, stem, and leaf of *A. marina* is presented as follows in Figure 4d. The translocation and incorporation processes had a higher rate at the beginning of the modeling period. The translocation process rate was observed to have increased at the end of the period along with the extraction while the incorporation decreased. Moreover, *A. marina* is expected to overcome the toxicity of pollutants in addition to having the accumulation ability. The toxic effects are usually attenuated through dilution which involves the plants storing much water in their bodies to dilute the concentration and reduce the toxicity of heavy metals. This normally occurs in the leaves followed by a process of leaf thickening or succulence. Another step that can be implemented by *A. marina* is excretion which involves storing heavy metal toxic materials in old tissues such as old leaves or easy-to-peel stems (Mulyadi et al., 2009).

The validation results of the Pb phytoremediation model in the *S. caseolaris, R. stylosa, A. alba,* and *A. marina* mangrove species at the Wonorejo River Estuary were as follows:

a) Structural validation

The four species have a similar root BCF value which was found to be < 1 from the beginning to the middle of the simulation period (2022–2032) and this means they were not included in the hyperaccumulator category. This was mainly because, according to Baker et al. (1989) and Ye-Tao Tang et al. (2009), the threshold for hyperaccumulator plants to accumulate Pb was 1,000 mg/kg, but the



(a) (b) (c) (d)

Figure 4. Simulation results of the Pb phytoremediation process model in (a) *S. caseolaris*, (b) *R. stylose*, (c) *A. alba*, (d) *A. marina* and its relationship with the root and leaf BCF values

structure validation conducted on the first 5 years of the simulation period (2022–2027) was recorded to be <1,000 mg/kg. The results presented in the model diagram of Figure 5 represent the causal relationship in the Pb phytoremediation by the four mangrove species and this indicated the model was structurally categorized as valid.

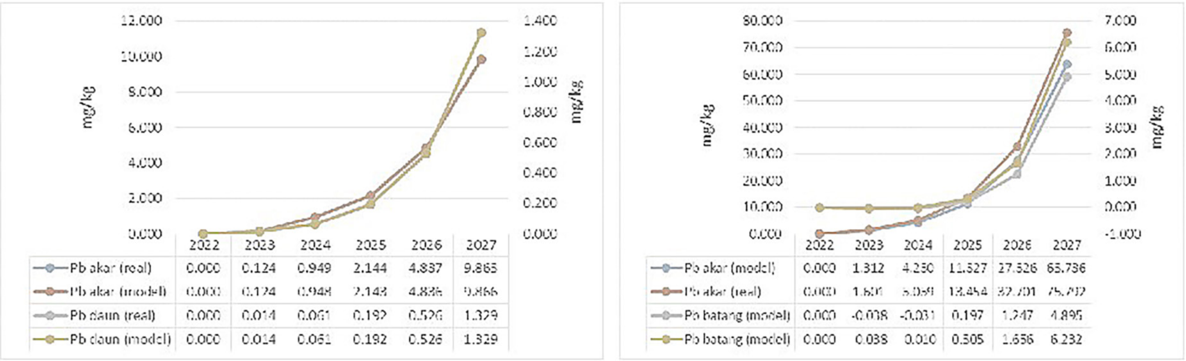
b) Value validation

The value validation was conducted by calculating MAPE. A model was stated to be valid when the MAPE value was < 30%. It was discovered that the MAPE value for the Pb phytoremediation model by *S. caseolaris* and *R. stylosa* was < 30% and this means it is valid. Meanwhile, the value for *A. alba* and *A. marina* model was >30%, indicating it has a fairly good or adequate forecasting validity because it is between 25–50%.

Model sensitivity test

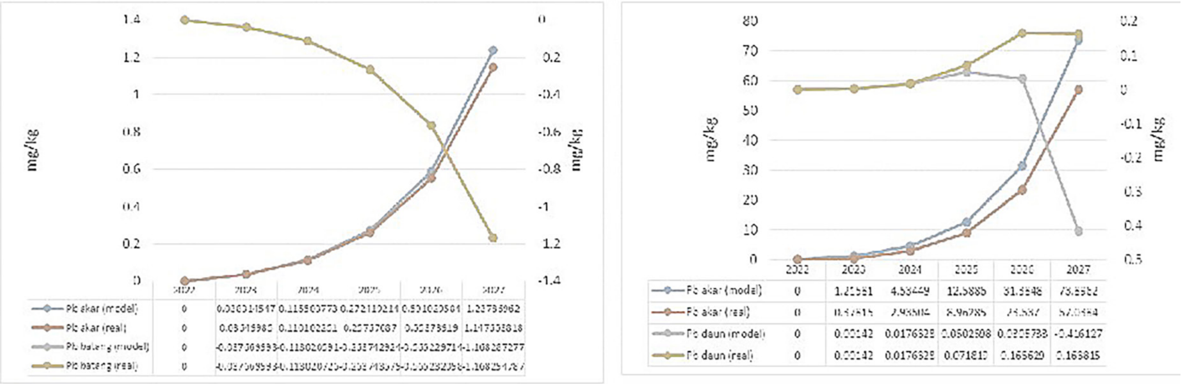
The sensitivity test was conducted on exogenous variables in an independent and controlled system to determine the factors with significant effects on the changes in the system. The results showed that the variables with a significant effect on the changes in the phytoremediation system are pH and Pb input. The resistance of the model to changes in existing variables was determined through a 50% decrease in the pH value and a 100% increase in the Pb input. The test results for the 4 system models were presented as follows in Figure 6.

It was discovered that the model has resilience as indicated by the similarity in the pattern formed between the simulation and sensitivity test results. The dynamic system analysis of the Pb phytoremediation process in the four mangrove species showed that the Pb values accumulated in environmental media and plant tissues are as follows. Table 6 showed that *R. stylose* had the highest accumulation value in environmental media and plant tissue. This means abiotic factors are affecting the growth and development of mangrove plants as well as their phytoremediation process of heavy metals. The data used for the model showed that the environmental factor values in the *R. stylose* habitat were quite good values for the growth and development of the mangroves.



Mangrove *S. caseolaris*

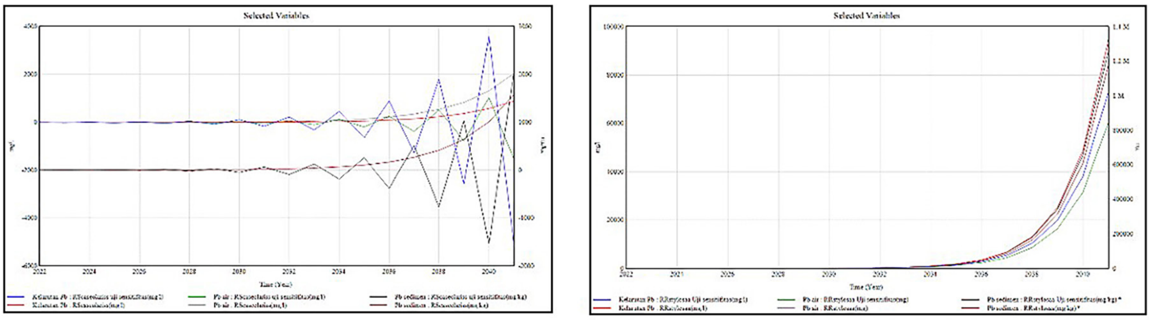
Mangrove *R. stylosa*



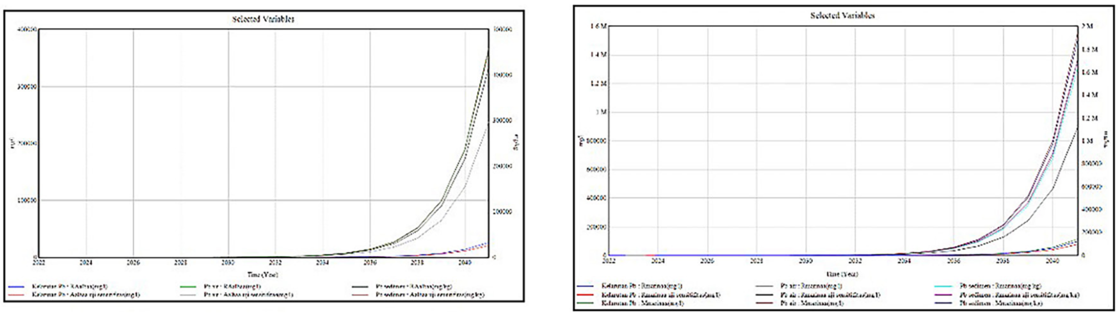
Mangrove *A. alba*

Mangrove *A. marina*

Figure 5. Structure validation results for the mangroves in the Wonorejo River estuary



Mangrove *S. caseolaris* Mangrove *R. stylosa*



Mangrove *A. alba* Mangrove *A. marina*

Figure 6. Sensitivity test results for the mangroves at the Wonorejo River estuary

Table 6. Pb Concentration values at the end of the modeling period (2041)

Species of mangrove	Concentration of Pb				
	Water (mg/L)	Sediment	Roots	Stems	Leaves
		(mg/kg)			
Avicennia alba	397,540.83	90,407.9	25,288.73	3.99^{e+06}	804.15
Sonneratia caseolaris	2,049.03	1,579.9	110,887	34,540	35.045
Rhizophora stylosa	1,329.110	1,509.790	2,054.110	3,393.950	-995,308
Avicennia marina	160,662.32	169,123	2.51×10^6	3.99^{e+06}	-2.91^{e+06}

This was indicated by the water pH of 7.5 which was close to normal pH while acidic water has the ability to cause very low decomposer activity which subsequently affects vegetation growth due to a lack of nutrient or mineral supply (Poedjirahajoe, 2019). Moreover, the BOD and COD values at 13.6 mg/L and 50 mg/L, respectively, were smaller compared to other species in the vicinity. They were determined based on the presence of organic matter contained in the waters which can be degraded by microorganisms and mangrove substrates to become nutrients needed for growth and development. Furthermore, BOD and COD values are negatively correlated to the dissolved oxygen (DO) value and this means the *R. stylosa* habitat had a higher DO value compared to the others and this further confirms the decomposition of organic matter in the habitat by decomposers. The content of the decomposed organic matter increases the ability of the mangroves to accumulate heavy metals. It was also observed that the concentration of organic matter is higher in the soil and sediment of the *R. stylose* habitat compared to the *Avicennia* habitat (Alongi, 2009). This explains that *R. stylose* has higher Pb accumulation value compared to the other three species.

CONCLUSIONS

Based on the results, the dynamic system of the phytoremediation process of Pb by the four mangrove species in the Wonorejo river estuary, it obtained Pb can be accumulated in environmental media and plant tissues. A behavioral mechanism pattern was formed based on the relationship between the environmental factors, Pb concentration, and the phytoremediation ability of the mangroves with time. This pattern affected the root and leaf BCF values of each mangrove. The MAPE of Pb phytoremediation of four mangrove species showed that model was categorized as fairly good with a valid forecast. The highest accumulation value in plant tissue was dominated by mangrove species of *R. stylose*. The environmental parameter values at habitat of *R. stylose* were in good condition for the growth of the mangroves. The system dynamics predicted that the highest concentrations of Pb in water, roots, and stems in 2041 were in *R. stylose* at 1,329,110 mg/L, 2,054,110 mg/kg, and 3,393,950 mg/kg, respectively.

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REFERENCES

1. Alamalik, L. 2004. Tutorial Pengenalan Software Vensim PLE. https://docplayer.info/66678080-Tutorial-pengenalan-software-vensim-ple.html
2. Alongi, D.M. 2009. The Emergetics of Mangrove Forest. Springer Science, Bussines Media B.V. Australia.
3. Annie, M.P.A., Sigua G.C. 2013. Phytoremidiation: A Green Technology to Remove Enviromental Pollutants. American J. Climate Change. 2(1): 71-86.
4. Balai Lingkungan Hidup Kota Surabaya. 2012. Laporan Pengendalian Pencemaran Kawasan Pantai dan Pesisir Tahun 2012. Badan Lingkungan Hidup Kota Surabaya, Surabaya.
5. Brass, G.M., Strauss W. 1981. Air Pollution Control. John Willey & Sons. New York.
6. Chen, M., Qin, X., Zeng, G., Li, J. 2016. Impact on Human Activity Modes and Climate on Heavy Metal Spread in Groundwater are Biased. Chemosphere 152, 439-455.
7. Darmono. 2001. Lingkungan Hidup dan Pencemaran: Hubungannya dengan Toksikologi Senyawa Logam. UI-Press. Jakarta.
8. Dewi, N.K. 2004. Penurunan Derajat Toksisitas kadmium terhadap Ikan Bandeng (Chanos chanos Forskal) Menggunakan Enceng Gondok (Eichhornia crassipes, (Mart.) Solms) dan Fenomena Transpornya. (Tesis). Universitas Diponegoro. Semarang.
9. Diliarosta, S. 2018. Fitoremediasi Logam Timbal (Pb) Menggunakan KIambang (Salvinia molesta) pada Ambang Batas, Kualitas Air Irigasi. Jurnal Semesta, 1(1), 29-33.
10. Fadillah, S., Rinidar, T., and Armansyah T. R. 2017. Cemaran Logam Berat Timbal (Pb) pada Daging Ikan Cendro (*Tylosurus crocodilus*) di Pesisir Krueng Raya Kabupaten Aceh Besar. 1(3), 391-397.
11. Febriana, E. 2017. Kandungan Logam Berat Timbal (Pb) pada Akar dan Daun Mangrove Avicennia Marina (Forsk) di Kawasan Mangrove Wonorejo Rungkut, Surabaya Jawa Timur. Tugas Akhir. Universitas Brawijaya. Malang.
12. Feliana, N.E. 2016. Analisis Kandungan Logam Berat Timbal (Pb) pada Akar dan Daun Mangrove Sonneratia caseolaris di Muara Sungai Porong, Jabon, Sidoarjo. Tugas Akhir. Universitas Brawijaya. Malang.
13. Forrester, J.W, Senge Peter M.. 1980. Test for Building Confidence in System Dynamics Model. TIMS Studies in the Management Sciences
14. Handayani, T. 2006. Bioakumulasi Logam Berat Dalam Mangrove *Rhizophora mucronata* dan *Avicennia marina* di Muara Angke Jakarta. Balai Teknologi Lingkungan Badan Pengkajian dan Penerapan Teknologi. Jakarta.
15. Hardiani, H. 2009. Potensi Tumbuhan Dalam Mengakumulasi Logam Cu Pada Media Tanah Terkontaminasi Limbah Padat Industri Kertas. *Bioscience*, 44 (1), 27–40
16. Irawanto, R., Mangkoedihardjo, S. 2015. Fitoforensik Logam Berat (Pb Dan Cd) pada Tumbuhan Akuatik (*Achantus ilicifolius* dan *Coix lacryma-Jobi*). Jurnal Purifikasi, 15(1), 55–66.
17. Lufthansa, U.M., Titah, H.S., Pratikno, H. 2021. The Ability of Mangrove Plant on Lead Phytoremediation at Wonorejo Estuary, Surabaya, Indonesia. Journal of Ecological Engineering. 22(6), 253–268.
18. MacFarlane, G.R., Burchett, M.D. 2001. Photosynthetic Pigments and Peroxides Activity as Indicators of Heavy Metal Stress in the Grey Mangrove Avicennia marina (Forsk.) Veirh. Marine Pollution Bulletin. 42: 233-240
19. Martin, S, Griswold, W. 2009. Human health effects of heavy metals. Environmental Science and Technology Briefs for Citizens; 15, 1–6.
20. Mellem, J.J., Baijnath, H., Odhav, B. 2012. Bioaccumulation of Cr, Hg, As, Pb, Cu and Ni with the ability for hyperaccumulation by Amaranthus dubius. African Journal of Agricultural Research. 7(4): 591-596, doi: 10.5897/AJAR11.1486
21. Mulyadi E., Laksmono R., D. Aprianti D. 2009. Fungsi Mangrove Sebagai Pengendali Pencemar Logam Berat. Envirotek: Jurnal Ilmiah Teknik Lingkungan, 1, 33–39

22. Mulyadi, E. R., Laksmono, D. Aprianti D. 2009. Fungsi Mangrove Sebagai Pengendali Pencemar Logam Berat. Envirotek: Jurnal Ilmiah Teknik Lingkungan, 1, 33–39.
23. Napaldet, J. T., Bout, E. I. Jr. 2019. Diversity of aquatic macrophytes in Balili River, La Trinidad, Benguet, Philippines as potential phytoremediators. Biodiversitas 20(4), 1048–1054.
24. Nastiti, W.A.N. 2016. Hubungan Kadar Logam Berat Cu pada Air, Sedimen, Mangrove *Avicennia marina*, dan Kerang *Anadara granosa* dengan Kerapatan Mangrove *Avicennia marina* di Wonorejo, Surabaya. Skripsi. Universitas Brawijaya. Malang.
25. Navabi, E. Daniell, K.A. Najafi, H. 2016. Boundary Matters: The Potential of Sistem Dynamics to Support Sustainability?. Journal of Cleaner Production, 140, 312–323. http://dx.doi.org/10.1016/j.jclepro.2016.03.032
26. Poedjirahajoe, E. 2019. Ekosistem Mangrove (Karakteristik, Fungsi dan Dinamikanya). Gosyen Publishing. Yogyakarta
27. Rachmawati, R., Yona, D., Kasitowati, R.D. 2018. Potensi mangrove *Avecennia alba* sebagai agen fitoremediasi timbal (Pb) dan tembaga (Cu) di Perairan Wonorejo, Surabaya. *Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan*, 7(3), 227–236. DOI: 1013170/depik.7.3.10555
28. Richardson, G.P. dan Pugh, A.L. 1981. Introduction to Sistem Dynamics Modeling with Dynamo. *MIT Press/Wright-Allen series in sistem dynamics*. Cambridge. ISBN: 978-0-262-18102-0
29. Salih N.M., Ahmed I.K., Ghafoor A.M.R., Zana H.A. 2014. Bioaccumulation, Enrichment and Translocation Factors of some Heavy Metals in *Typha Angustifolia* and *Phragmites Australis* Species Growing along Qalyasan Stream in Sulaimani City /IKR. Journal of Zankoy Sulaimani- Part A, 16 (4): 93–109.
30. Sopyan, R. Sikanna, Sumarni, N.K. (2014), Fitoakumulasi merkuri oleh akar tumbuhan bayam duri (*Amarantus spinosus* Linn.) pada tanah tercemar. Online Journal of Natural Science. 3(1), 31–39, http://dx.doi.org/10.2012/.
31. Sudarmaji, J., Mukono and Corie, I.P. 2006. Toksikologi logam berat B3 dan dampaknya terhadap kesehatan. *Jurnal Kesehatan Lingkungan*, 2(2), 129–142.
32. Sutamihardja. 2006. *Toksikologi Lingkungan*. Buku Ajar Program Studi Ilmu Lingkungan, Universitas Indonesia, Jakarta.
33. Tavakkoli, E., Rengasamy, P., McDonald, G.K. 2010. High concentrations of Na^+ and Cl^- ions in soil solution have simultaneous detrimental effects on growth of faba bean under salinity stress, Journal of Experimental Botany, 61(15), 4449–4459.
34. Titah, H.S, Pratikno, H., Harnani, B.R.D. 2021. Uptake of copper and chromium by *Avicennia marina* and *Avicennia alba* at Wonorejo Estuary, East-coastal area of Surabaya, Indonesia. Regional Studies in Marine Science. 47, 101943.
35. Usman, S. 2013. Distribusi Kuantitatif Logam Berat Pb Dalam Air, Sedimen dan Ikan Merah (*Lutjanus erythropterus*) di Sekitar Perairan Pelabuhan Parepare. Thesis University of Hasanuddin. Indonesia.
36. Wahwakhi, S. 2015. Kajian *Avicennia alba* sebagai Agen Fitoremediasi Upaya Mengurangi Konsentrasi Logam Berat Pb di Ekosistem Mangrove Kelurahan Wonorejo, Kota Surabaya. Thesis. University of Brawijaya. Indonesia.
37. Ye-Tao, T., Rong-Liang, Q., Xiao-Wen, Z., Rong-Rong, Y., Fang-Ming, Y., Xiao-Yong, Z. 2009. Lead, Zinc, Cadmium Hyperaccumulation and Growth Stimulation in *Arabis paniculata* Franch. Environmental and Experimental Botany. 66, 126–134.
38. Yoon, J., Xinde, C., Qixing, Z., Ma, L.Q. 2006. Accumulation of Pb, Cu and Zn in native plants growing on a contaminated Florida site. Science of the Total Environment. (2–3), 456–464, http://dx. doi.org/ 10.1016/j.scitotenv.2006.01.016.
39. Zainal, A., dan Diani, F. 2009. Fraksinasi Logam Berat Pb, Cd, Cu dan Zn dalam Sedimen dan Bioavailabilitasnya bagi Biota di Perairan Teluk Jakarta. Ilmu Kelautan, 14(1), 27–32.