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Material Flow Analysis and Risk Assessment of Wastewater and Sludge Treatment in Bangkok, Thailand

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Abstract

This research evaluated the wastewater and sludge characteristics, and material flows in Nongkhaem Water Environment Control Plant. The constituent removal efficiencies of the wastewater treatment plant and human health risks (for children and adults) caused by sludge utilization were determined. The results from the Material Flow Analysis showed that the wastewater treatment process can remove nutrients efficiently. The removal rate of TOC, T-N, and T-P were 72%, 62%, 72% respectively. In case of heavy metal, the removal rate of heavy metals was between 62-87%. This means that it can reduce human health risks from heavy metals in treated water. Heavy metals content in sewage sludge can be ranked according to mean concentrations in the following order: Zn > Cu > Cr > Ni > Pb > As > Mo > Se > Hg > Cd. Cu, Zn and Cr were the top three highest heavy metals that caused non-carcinogen health risks for both children and adults. Heavy metals in dry-based sewage sludge would be toxic for children's health (non-carcinogen health risks) but not for adults. The carcinogenic risks from sludge utilization were under the safe limit for both children and adults.

Keywords : Material flow analysis; Human health risk assessment; Wastewater treatment plant; Removal efficiencies; Carcinogenic risk; Non-carcinogenic risk

Introduction

Advanced technologies of modern wastewater treatment systems for improving the urban environment have been developed for various objectives. Currently, Bangkok Metropolitan Administration (BMA) has 20 wastewater treatment plants, which cover approximately 40% of the area. Bangkok planned to increase the number of large-scale wastewater treatment plants (WWTPs) to 30 plants in 2040 because of the rapid population growth. However, Bangkok had technical issues and water pollution abuses from the existing treatment facilities [1]. Moreover, there is currently no direct sewerage control legislation for water treatment services in BMA. Both the Enhancement and Conservation of National Environmental Quality Act 1992 and Environmental Quality Promotion and Prevention Act 1992 pointed out that wastewater should be treated. But policies at the national level do not have operating procedures for Bangkok's sewerage control. On the other hand, Sewage sludge is a rich source of phosphorus and nitrogen [2, 3], that is suitable for agriculture use. Moreover, sewage sludge was also utilized in alternate ways such as mono-incineration of sludge, sludge co-incineration with municipal solid waste, raw materials for brick or cement production [4]. However, sewage sludge from WWTPs consists of many kinds of heavy metal [5, 6]. The existing literature reported that sludge has high human health risks such as non-carcinogenic and carcinogenic risks [7] and is not recommended to be used as fertilizer because the amounts of some heavy metals exceed the regulation of the country [8]. Based on the USEPA Part 503 rule, ingestion, dermal contact, and inhalation are the main pathways of human exposure to heavy metals in sewage sludge. The sludge utilization may cause non-carcinogenic and carcinogenic risks from different pathways such as unintentional ingestion by children [9, 10], dermal contact of human from utilizing sludge-based products such as fertilizer or soil conditioner [11]. Furthermore, two forms can be inhaled by humans: volatilized sewage sludge and particles (dust) [12] that may happen with burning or volatilizing.

The objectives of the research are i. to understand and evaluate the wastewater and sludge characteristics, and material flows in a WWTP in Bangkok, Thailand by using material flow analysis (MFA); ii. to assess the wastewater's efficiency of a WWTP in Thailand; and iii. to assess the human health risks (for children and adults) caused by heavy metals from sludge utilization.

Methodology

Sampling and Measurement

The WWTP considered in this research is Nongkhaem Water Environment Control Plant which treat water by conventional activated sludge with nutrients removal by vertical loop reactor (VLR). This study performed sampling the WWTP for 14 times in total from September 2017 to July 2018. Other important information was gathered from the daily sampling reports. For each sampling, 9 samples including influent, effluent, thickening process supernatant, dewatering process supernatant, activated sludge (WAS), thickened sludge, digested sludge, sludge from other WWTPs and dewatered sludge were collected. In total, 126 samples were collected and analyzed. Other information such as the flow rate were collected from a daily report. In this study, the influent is defined as the wastewater before entering the aeration tank (after coarse screen and grit chamber processes) based on the set up by the WWTP so that the measurements could be comparable with the results measured by the WWTP. Both influent (in this study) and conventional influent are indicated in Figure 1.

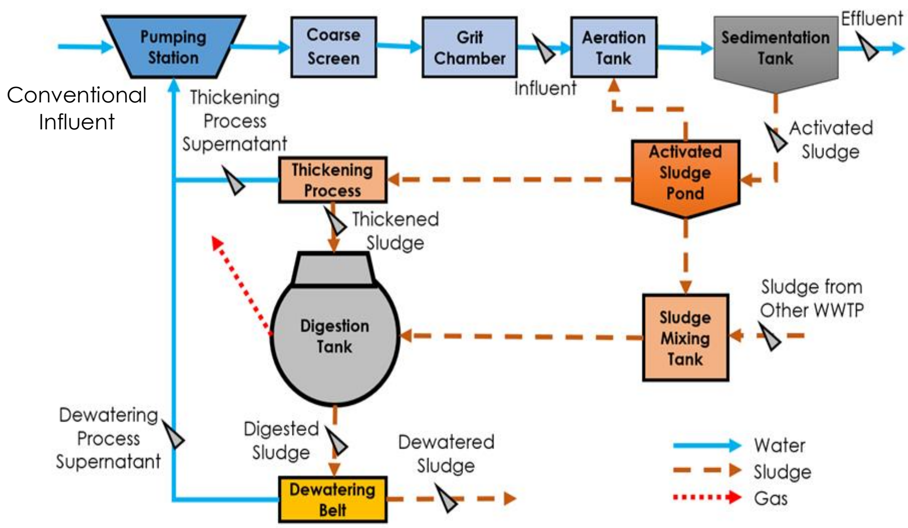

Figure 1 Schematic diagram of Nongkhaem WWTP, Bangkok, Thailand. The tilted triangle indicates where samples were taken

Suspended solid (SS), total solid (TS), volatile total solid (VTS), fixed total solid (FTS), nitrogen, phosphorus, sulfur, hydrogen, oxygen, total organic carbon (TOC) and 10 heavy metals (As, Cd, Cr, Cu, Pb, Hg, Ni, Mo, Se, and Zn) were considered and each sample was measured in duplicate.

SS, TS, VTS and FTS measured based on Wastewater Examination Method, 2012 of Japan Sewage Work Association [13], TOC measured based on Sediment survey method of Ministry of the Environment, Japan [14] by using Shimadzu TOC-V CSH for liquid samples and SSM-5000 for solid samples.

Nitrogen, Sulfur, Phosphorus, Hydrogen and Oxygen were measured using Lab Center XRF-1800 of Shimadzu corporation to measure the percentage of element concentration and calculation in mg/kg unit.

As, Cd, Cr, Cu, Pb, Ni, Mo, Se, and Zn, pre-treatment of samples before measurement of samples were conducted by following Wastewater Examination Method, 2012 of Japan Sewage Work Association [13]. After the pretreatment, ICP IRIS Intrepid Duo of Thermo Fisher Scientific Inc. for measuring concentration was used. For Hg, we used MA-2000 of Nippon Instruments Corporation for measuring concentration.

Material Flow Analysis (MFA)

Material Flow Analysis was used to analyze the daily material flow based on data from sample measuring and daily reports from Nongkhaem Water Environment Control Plant using STAN 2.6 software that was developed by Vienna University of Technology that performing MFA according to the Austrian standard ÖNORM S 2096. STAN calculates the best fitted values iteratively using a successive linear data reconciliation process and the Gauss' Law of error propagation. The standard uncertainty was calculated by combining the standard uncertainty for the following factors: variation in mass flow rate, total solid content, concentration of each element per mass of total solids, and accuracy of measurements. [15, 16]. This study used each process' mean concentration values from the sampling period as inputs of the STAN 2.6 program. The uncertainty values were represented as standard errors of sample's mean. The system boundary of material flow analysis was set on wastewater treatment processes including the anaerobic digestion processes and sludge treatment processes. After implementing mass balanced, we compared removal efficiencies of target parameters.

Human Health Risk Assessment (HHRA)

HHRA was carried out to estimate the potential risks and human health effects of heavy metals in sludge utilizations. The calculation approach from USEPA to assess non-carcinogenic and carcinogenic risks (for adults and children) from sludge usage was applied [17]. This study assessed dried-based (0% water contents) dewatered sludge in Nongkhaem Environment Control Plant. We calculated the average daily dose (ADD) of potentially toxic metal via ingestion, inhalation, and dermal for both children and adults in dry-based sludge by using the following equations. The exposure factor and values for estimating the intake value and risks are given in Table 1.

$$ADD_{inges} = \frac{C \times IR_{inges} \times EF \times ED}{BW \times AT} \times CF \quad (1)$$

$$ADD_{inhal} = \frac{C \times IR_{inhal} \times EF \times ED}{PEF \times BW \times AT} \quad (2)$$

$$ADD_{derm} = \frac{C \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times CF \quad (3)$$

USEPA defined 10 elements as heavy metals which included As, Cd, Cr, Cu, Hg, Pb, Ni, Mo, Se, and Zn [12, 17]. The heavy metals causing health risks were categorized into non-carcinogenic elements (Cr, Cu, Hg, Pb, Ni, Mo, Se, and Zn) and carcinogenic risk elements (As and Cd) [20].

Table 1 Description and values of factors used in exposure assessment calculation

Factor	Description	Unit	Values		Source
			Children	Adult	
C	Exposure-point concentration	mg/kg	-	-	This study
IR_{ingest}	Ingestion rate	mg/day	200	100	[17]
IR_{inhale}	Inhalation rate	mg/day	7.6	20	[17]
EF	Exposure frequency	Day/year	350	350	[17]
ED	Exposure duration	years	6	24	[18]
CF	Conversion factor	kg/mg	1×10^{-6}	1×10^{-6}	[17]
PEF	Particle emission	m^3/kg	1.36×10^{9}	1.36×10^{9}	[17]
BW	Average body weight	kg	16	70	[17]
SA	Exposure skin surface area	cm^2	1600	4350	[18]
AF	Skin adherence factor	mg/cm.day	0.2	0.7	[17]
ABS	Dermal absorption factor	No unit	0.001	0.001	[19]
AT	Average time	day	Carcinogen = 70×365 Non-carcinogen =ED×365		[17]

Non-Carcinogenic Risk Assessment

Hazard Quotient (HQ) of a single heavy metal and Hazard Index (HI) for the non-carcinogenic risks' assessment are determined using the following equations:

$$\mathrm{HQ} = \frac{ADD}{RfD} \quad (4)$$

$$HI = \sum HQ = \sum \frac{ADD}{RfD} \quad (5)$$

Carcinogenic Risk Assessment

Exposure dose of heavy metal for carcinogenic effects was multiplied by carcinogen risks value (RISK). This study uses the following formula to calculate RISK.

$$RISK = \sum ADD \times SF \quad (6)$$

Reference dose (RfD) for the non-carcinogenic risks assessment and slope factor (SF) for the carcinogenic risks assessment that were used for calculation are: Cr = 0.005 mg/kg/day, Cu = 0.004 mg/kg/day, Pb = 0.038 mg/kg/day, Hg = 0.0003 mg/kg/day, Ni = 0.02 mg/kg/day, Se = 0.005 mg/kg/day, Zn = 0.03 mg/kg/day, Mo = 0.005 mg/kg/day, As = 1.5 kg.day/mg and Cd = 6.1 kg.day/mg [20].

Limitation of the Human Health Risk Assessment

In this study, we sampled only sludge from Nongkhaem Environment Control Plant, while the products or matters used or made from sludge were not sampled. The concentrations from sludge measurement values were directly considered in the human health risk assessment.

Results and Discussions

Material Flow Analysis

The mass balance was successfully constructed for all parameters and elements analyzed in this study due to the analytical methods and tool's limitations. Figure 2-5 showed the mass balance diagrams of selected water quality parameters; and Figure 6-9 showed the mass balance diagrams of selected heavy metals through Nongkhaem Environment Control Plant.

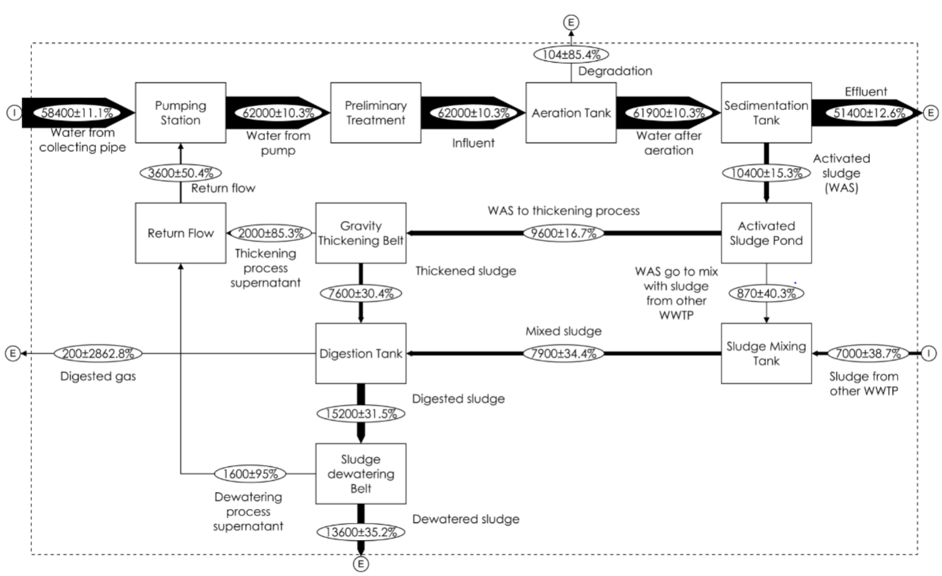

Figure 2 Average daily material flow of TS through Nongkhaem Environment control plant in kg/day

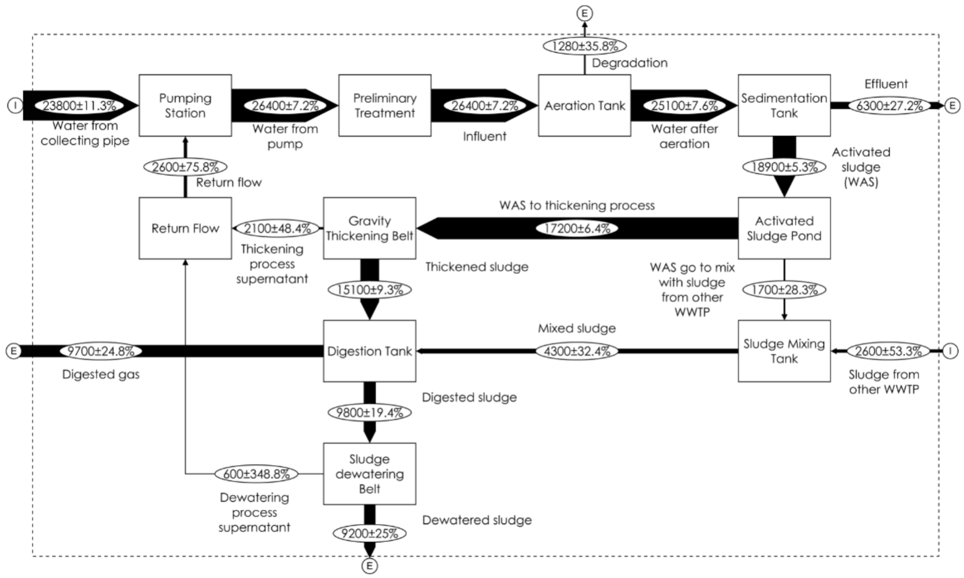

Figure 3 Average daily material flow of TOC through Nongkhaem Environment control plant in kg/day

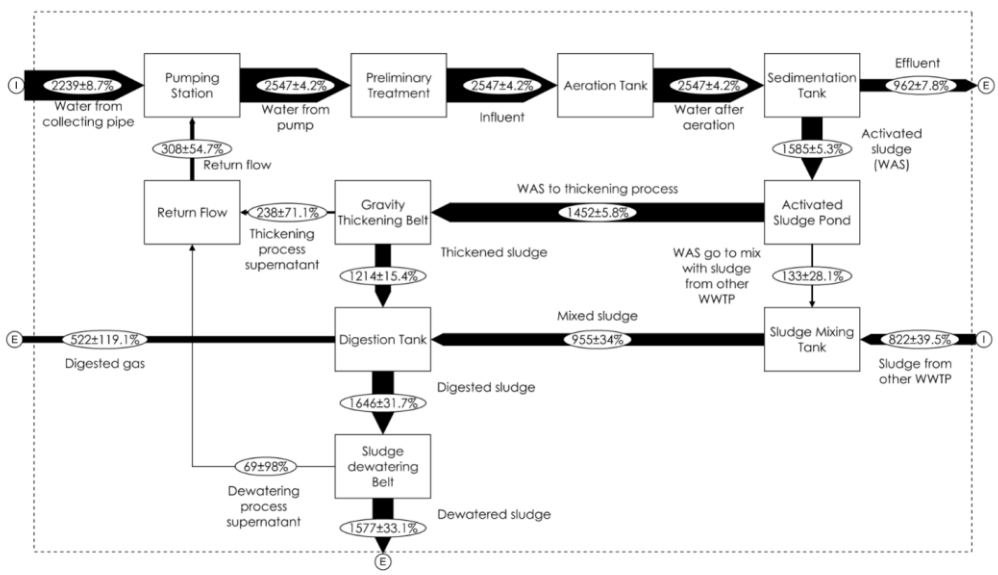

Figure 4 Average daily material flow of T-N through Nongkhaem Environment control plant in kg/day

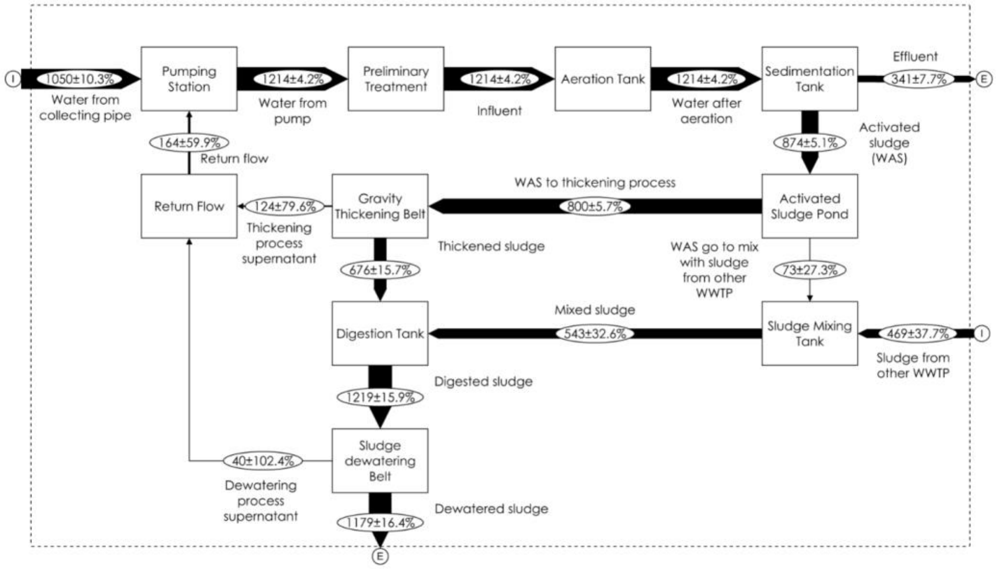

Figure 5 Average daily material flow of T-P through Nongkhaem Environment control plant in kg/day

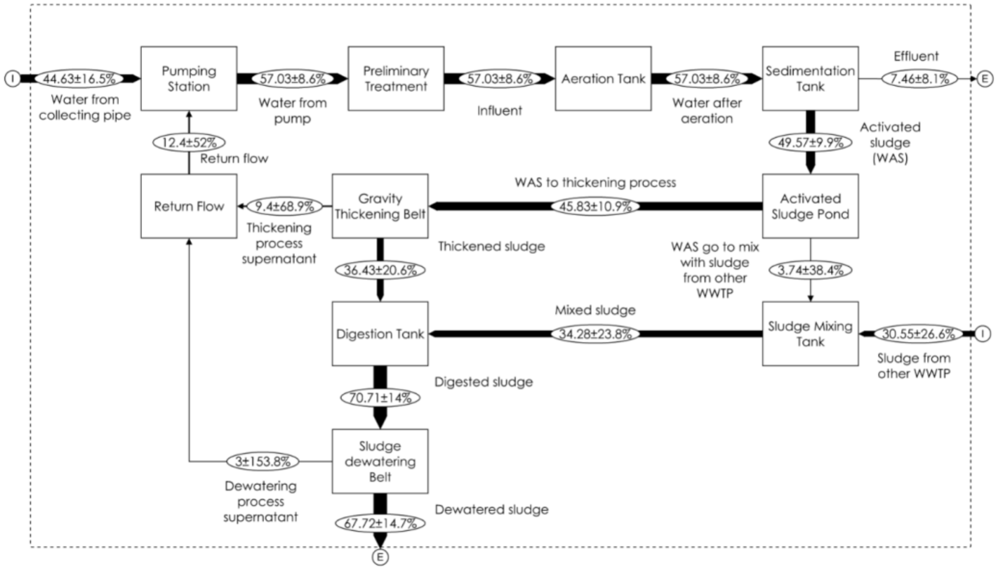

Figure 6 Average daily material flow of Cu through Nongkhaem Environment control plant in kg/day

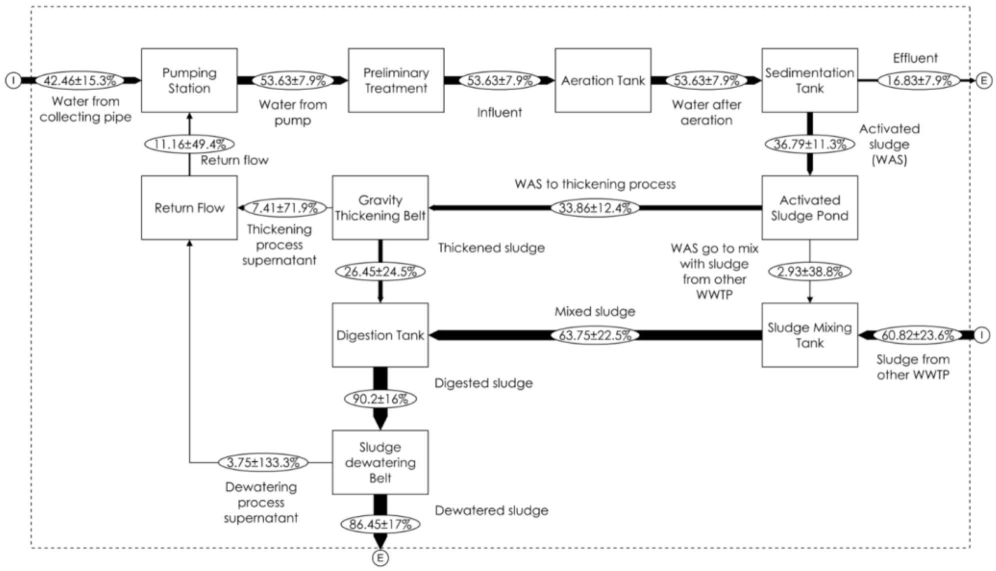

Figure 7 Average daily material flow of Zn through Nongkhaem Environment control plant in kg/day

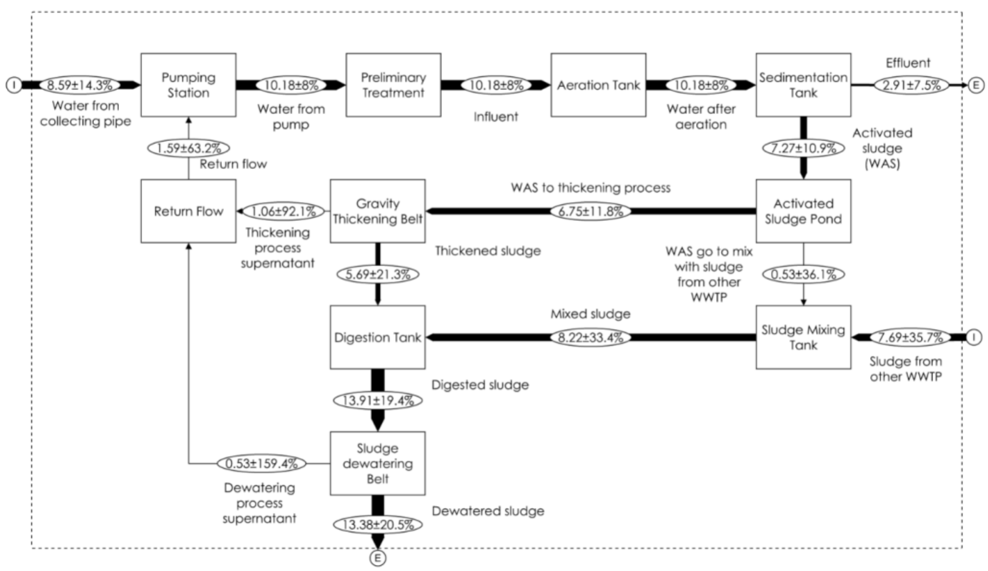

Figure 8 Average daily material flow of Cr through Nongkhaem Environment control plant in kg/day

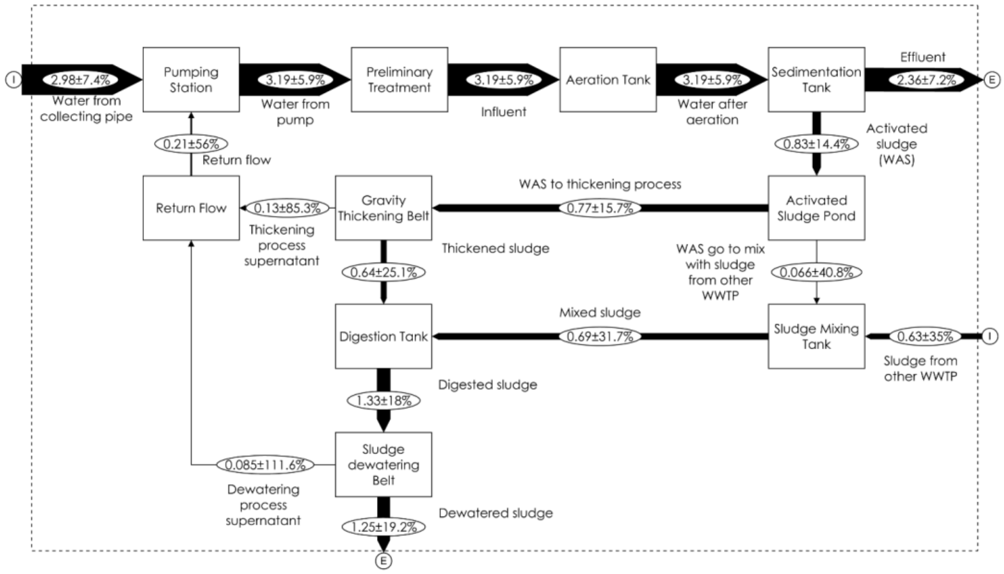

Figure 9 Average daily material flow of As through Nongkhaem Environment control plant in kg/day

Wastewater Treatment Process

During the sampling period, 143,356 m^3/day of wastewater had 9,400 kg/day of SS, 62,000 kg/day of TS, 29,000 kg/day of VTS, and 33,000 kg/day of FTS entering the Nongkhaem Environment Control Plant on average. After treated, had 141,220 m^3/day of treated water will released with 970 kg/day of SS, 51,000 kg/day of TS, 22,000 kg/day of VTS and 29,000 kg/day. During the wastewater treatment process, 90% of SS was removed. 11% of SS was removed by the biological treatment in the aeration tank and activated sludge. 79% of SS was removed by polymer flocculation and absorption in sedimentation process and settled into the bottom of the sedimentation tank before moving to the sludge treatment process. In the case of TS, VTS, and FTS, 0.2% of TS and 0.4% of VTS were removed by the biological treatment in the aeration tank and activated sludge's disinfection, whereas FTS was not affected by the biological treatment. 17% of TS, 22% of VTS, and 13% of FTS were removed by polymer flocculation, sedimentation, and absorption in the sedimentation process and settled into the bottom of the sedimentation tank before moving to the sludge treatment process. H, S, O, and TOC were removed due to the biological treatment and activated sludge disinfection by 22%, 19%, 6%, and 5%, respectively, but T-N and T-P didn't lose the mass from this treatment process. In the sedimentation tank, H, S and O were removed only 35%, 9% and 17%. This is relatively a small rate when compared with other elements such as TOC (72%), T-N (62%), and T-P (72%). During the sampling period, MFA result showed that heavy metal removal rates were between 62-87% from removing from wastewater by polymer flocculation and absorption in sedimentation process and going to sludge treatment process. Heavy metals didn't remove or lose in the biological treatment in the aeration tank. Mo and As were not significantly removed by was removed by polymer flocculation, sedimentation, and absorption in sedimentation process in the wastewater treatment process with removal rates of 55% and 26%, respectively. In the portion of influent, 86-96% of water quality parameter's particulars and nutrient came from conventional influent, and 4-14% from the sludge treatment process returned to the wastewater treatment process. In SS's case, 68% of SS came from conventional influent and 32% came from the sludge treatment process returned to the wastewater treatment process. In the case of heavy metals, 75-93% of heavy metals came from conventional influent, and 7-25% of heavy metals from the sludge treatment process returned to the wastewater treatment process.

When compared Nongkhaem Environment Control Plant's removal rates from this research and data from the Department of Drainage and Sewerage [21] in 2015 to 2020 on SS, T-N, and T-P, the compared removal rates of all parameters are not significantly different. The rates of heavy metals were higher than the average of Bangkok [22]. Behavior and character of heavy metal removal in this work were similar with the same range of the removal rates when compared with Yang [23], who conducted similar research presenting the removal rates of WWTP's which operated by the conventional activated sludge method.

Sludge Treatment Process

Nongkhaem Environment Control Plant treats wastewater by the standard activated sludge method. 888 m^3/day of wasted activated sludge was sent to the sludge treatment process to treat dewatered sludge. Wasted activated sludge was separated into 2 ways; one of the ways is going to thickening process. This portion was 92% of waste-activated sludge. The other way is to mix with dewatered sludge from other WWTPs to adjust concentrations before the digestion process as 8% of waste-activated sludge. In the thickening process, after sludge thickened, around 79-88% of TS, VTS, FTS, elements, and heavy metals were accumulated in thickened sludge, and 12-21% will flow back to the wastewater treatment process with thickening process supernatant. Thickened sludge and mixed sludge blended in the digestion tank at half and half-rate and digested to be digested gas. In this portion, VTS, TOC, N, and H digested at a high rate of 25%, 50%, 24%, and 20% of sludge entering the digestion tank, respectively. We could see the digestion effect on other parameters or elements for a few rates, except for heavy metals. During the sampling period, 68 m^3/day of dewatered sludge was produced from Nongkhaem Environment Control Plant on average using a mechanical belt press method. 90-97% of target components accumulated in dewatered sludge and 3-10% of components flow back to the wastewater treatment process with thickening process supernatant. Meanwhile, S accumulated in dewatered sludge around 82% and 18% of S flow back to the wastewater treatment process with thickening process supernatant. When observing at the overview, 67-88% of water quality parameter's particulars and nutrients came from conventional influent in dewatered sludge and digested gas form, and 12-28% from the sludge treatment process returned to the wastewater treatment process. For the case of VTS, TOC, T-N, and H, they were associated with a high rate of digested in the digestion process for 22%, 45%, 22%, 18%, respectively. In heavy metals, 80-91% of heavy metals in the sludge treatment process accumulated in dewatered sludge, and 9-20% of heavy metals from the sludge treatment process returned to the wastewater treatment process and did not get the effect from the digestion process.

Uncertainty

Water quality parameters, elements, and heavy metals in the wastewater treatment flows were accompanied by an uncertainty range smaller than 10%. Supernatant separated process flows such as thickening and dewatering processes were accompanied by large uncertainties in the ranges larger than 70%. Especially in the dewatering process supernatant, the uncertainties were always higher than 100% because of the high fluctuation of concentrations in each sampling. The large uncertainty ranges were also observed in the flows calculated by subtraction such as digestion process and degradation in the aeration tank (often above 100%). The high uncertainties in these specific flows were also found in existing studies [24].

Human Health Risk Assessment

Heavy Metal Concentrations

The heavy metal concentrations in dewatered sludge from Nongkhaem WWTP in dry-based are presented in Table 2. The mean concentrations of heavy metals in dewatered sludge can be ranked in the following decreasing order: Zn > Cu > Cr > Ni > Pb > As > Mo > Se > Hg > Cd. Zn is the most abundant heavy metal, while Cd is the least abundant heavy metal in dewatered sludge. From the standard deviation, we found that Zn, Cu, and Cr have the obvious changes in concentrations. On the other hand, Cd is a heavy metal that has a small change in concentrations.

When compared the heavy metal concentrations with other countries, Thailand's heavy metal concentrations in dewatered sludge under this study were lower than the ones in the USA were in the same range as the ones in Asian countries (Japan and China); and were higher than the ones in Sweden.

Exposure Assessment

Exposure assessment of this study was conduct based on USEPA's A Plain English Guide to the EPA Part 503 Biosolids Rule that identified ingestion, inhalation, and dermal contact were the main pathway of human exposure to sludge [12]. Ingestion may occur from unintentionally ingestion of products from sludge such as fertilizer or soil conditioner. Inhalation may occur from volatile matter from sludge or particular from burning like incineration of sludge. Dermal contact may occur from touching the sludge or sludge products like fertilizer, soil conditioner, cement, or brick. Based on the results shown in Table 3, average daily dose (ADD) of heavy metals in dewatered sludge calculated based on mean values can be ranked in the decreasing order as Zn > Cu > Cr > Ni > Pb > Mo > Se > Hg > As > Cd for children and Zn > Cu > Pb > Cr > Ni > Mo > As > Se > Hg > Cd for adults. According to ADD that calculated from the mean, the highest ADD values for children and adults were recorded as Zn, Cu, and Cr in the decreasing order, except for ADD for DES in adults which is Zn, Cu, and Pb in the decreasing order. The lowest ADD value for all was Cd. From the results, exposure to all heavy metals for children was higher than adults. Furthermore, the total heavy metals exposure for children was 6.92 times higher than adults' mean values. This result represents the heavy metal exposure based on the same concentrations which were higher for children than adults, and the health effects of heavy metals in sludge were more dangerous for children than adults.

Non-Carcinogenic Health Risks

According to the results in Table 4. The mean values of HQ, Cu, Zn, and Cr are the top three heavy metals that cause the non-carcinogen health risks from highest to lowest for both children and adults for dewatered sludge. When considering the ratio of HI, Cu, Zn, and Cr have 72.14%, 11.53%, and 11.39% of the HI value for children, respectively, and have 69.03%, 11.03%, and 10.90% of the HI value for adults respectively. From the results of HQ calculation based on the mean heavy metal, HQ values can be ranked in the decreasing order as Cu > Zn > Cr > Hg > Ni > Pb > Mo > Se for children, while it can be ranked as Cu > Zn > Cr > Pb > Hg > Ni > Mo > Se for adults. The values of HQ_{ingest}, HQ_{inhal}, and HQ_{dermal} were lower than 1 for all heavy metals, except for HQ_{ingest} of Cu for children which are 2.83. This result showed no non-carcinogenic risks when adults and children were exposed to single heavy metal in sewage sludge via ingestion, inhalation, and dermal contact. However, the children had the non-carcinogen risks of Cu in mean via ingestion. From results, ingestion was the main pathway of heavy metal exposure in sewage sludge for adults and children.

Table 2 Dewatered sludge's heavy metal concentrations in mg/kg

Heavy Metal	Concentration (mg/kg)				
	Bangkok, Thailand (This study)	Taiyuan, China [6]	USA [25]	Sweden [26]	Japan [27]
	Mean (SD)	Mean (SD)	Mean	Mean	Mean
Cr	186.31 (20.17)	111.54 (49.91)	-	30	86.6
Cu	943.62 (195.58)	214.08 (54.30)	1720	314	338.6
Pb	74.53 (6.85)	50.84 (7.82)	350	16	44.3
Hg	2.28 (0.39)	2.80 (0.96	7.5	0.5	1
Ni	98.65 (10.95)	-	526	15	66.7
Se	2.53 (0.73)	-	24.2	-	3
Zn	1131.20 (150.77)	93.64 (21.86)	8550	496	823.8
Mo	5.75 (0.26)	-	86.4	-	7.8
As	15.33 (2.53)	16.69 (3.56)	49.2	-	12.3
Cd	1.33 (0.18)	0.68 (0.29)	11.8	0.7	2.7

Table 3 Average daily doses for adults and children of heavy metals in dewatered sludge

Heavy Metals	Adults (mg/kg/day)				Children (mg/kg/day)			
	ADD_{ingest}	ADD_{inhal}	ADD_{dermal}	ADD_{total}	ADD_{ingest}	ADD_{inhale}	ADD_{dermal}	ADD_{total}
Cr	2.55E-04	3.75E-08	7.77E-06	2.63E-04	2.23E-03	6.24E-08	3.57E-06	2.24E-03
Cu	1.29E-03	1.90E-07	3.94E-05	1.33E-03	1.13E-02	3.16E-07	1.81E-05	1.13E-02
Pb	8.93E-04	2.50E-08	1.43E-06	8.95E-04	8.93E-04	2.50E-08	1.43E-06	8.95E-04
Hg	3.12E-06	4.59E-10	9.50E-08	3.21E-06	2.73E-05	7.63E-10	4.37E-08	2.73E-05
Ni	1.35E-04	1.99E-08	4.11E-06	1.39E-04	1.18E-03	3.30E-08	1.89E-06	1.18E-03
Se	3.47E-06	5.10E-10	1.06E-07	3.57E-06	3.03E-05	8.48E-10	4.85E-08	3.04E-05
Zn	1.55E-03	2.28E-07	4.72E-05	1.60E-03	1.36E-02	3.79E-07	2.17E-05	1.36E-02
Mo	7.88E-06	1.16E-09	2.40E-07	8.12E-06	6.89E-05	1.93E-09	1.10E-07	6.90E-05
As	7.20E-06	1.06E-09	2.19E-07	7.42E-06	1.58E-05	4.40E-10	2.52E-08	1.58E-05
Cd	6.24E-07	9.18E-11	1.90E-08	6.43E-07	1.37E-06	3.81E-11	2.18E-09	1.37E-06
Sum	4.15E-03	5.04E-07	1.01E-04	4.25E-03	2.93E-02	8.19E-07	4.69E-05	2.94E-02

Table 4 Hazard Quotient (HQ), Hazard Index (HI) and RISK of heavy metals in dewatered sludge

Heavy Metals	Adults (mg/kg/day)				Children (mg/kg/day)			
	HQ_{ingest}	HQ_{inhal}	HQ_{dermal}	HQ_{total}	HQ_{ingest}	HQ_{inhal}	HQ_{dermal}	HQ_{total}
Cr	5.10E-02	7.51E-06	1.55E-03	5.26E-02	4.47E-01	1.25E-05	7.15E-04	4.47E-01
Cu	3.23E-01	4.75E-05	9.84E-03	3.33E-01	2.83E+00	7.90E-05	4.52E-03	2.83E+00
Pb	2.35E-02	6.57E-07	3.76E-05	2.35E-02	2.35E-02	6.57E-07	3.76E-05	2.35E-02
Hg	1.04E-02	1.53E-06	3.17E-04	1.07E-02	9.10E-02	2.54E-06	1.46E-04	9.11E-02
Ni	6.76E-03	9.94E-07	2.06E-04	6.96E-03	5.91E-02	1.65E-06	9.46E-05	5.92E-02
Se	6.93E-04	1.02E-07	2.11E-05	7.15E-04	6.07E-03	1.70E-07	9.71E-06	6.08E-03
Zn	5.17E-02	7.60E-06	1.57E-03	5.32E-02	4.52E-01	1.26E-05	7.23E-04	4.53E-01
Mo	1.58E-03	2.32E-07	4.80E-05	1.62E-03	1.38E-02	3.85E-07	2.21E-05	1.38E-02
HI	4.69E-01	6.61E-05	1.36E-02	4.82E-01	3.92E+00	1.10E-04	6.27E-03	3.93E+00
Heavy Metals	Adults (mg/kg/day)				Children (mg/kg/day)			
	$RISK_{ingest}$	$RISK_{inhal}$	$RISK_{dermal}$	$RISK_{total}$	$RISK_{ingest}$	$RISK_{inhal}$	$RISK_{dermal}$	$RISK_{total}$
As	1.08E-05	1.59E-09	3.29E-07	1.11E-05	2.36E-05	6.60E-10	3.78E-08	2.37E-05
Cd	3.81E-06	5.60E-10	1.16E-07	3.92E-06	8.33E-06	2.33E-10	1.33E-08	8.34E-06
RISK	1.46E-05	2.15E-09	4.45E-07	1.51E-05	3.20E-05	8.93E-10	5.11E-08	3.20E-05

Considering HI values from the mean for children and adults, the HI value of children was 3.92, which is higher than 1. The HI value of adults was 0.47, which is lower than 1. The HI value of children was higher than the HI value of adults approximately 8.34 times. The results showed that children had non-carcinogen risks from sewage sludge, while heavy metals in sewage sludge are toxic for children's health, but not for adults.

Carcinogenic Health Risks

The average daily doses of As and Cd via ingestion, inhalation, and dermal were calculated to assess the carcinogenic risks as shown in Table 4. According to the mean value, $RISK_{ingest}$, $RISK_{inhal}$, and $RISK_{dermal}$ values for As and Cd were lower than the safety limit of 1E-04, which proved no carcinogenic risk for both adults and children when they were exposed to As and Cd. Furthermore, as shown in Table 4, according to the mean value, the total carcinogen risks ($RISK_{total}$) of children were 3.20E-05 for dewatered sludge. The total carcinogen risks of the adults were 1.51E-05. The RISK was higher for children than adults. All values exceed the limit of 1E-05, but the values are still closed to 1E-05. The result showed both children and adults had the opportunity to suffer from the carcinogenic risks. Children suffered more carcinogenic risks than adults. When comparing the RISK value, the values for every pathway for Arsenic are larger than Cadmium. The result showed that Arsenic was the main heavy metal that caused the carcinogenic risks. When compared with the exposure pathway, ingestion was the main pathway for the carcinogenic risks. The second and third pathways were dermal and inhalation contact which is the same as the non-carcinogenic health risks.

Conclusions

Component characteristics and the fate of 20 parameters in the WWTP were conducted and proved by Material Flow Analysis. The results showed that the material flow analysis approach can be applied for components in the wastewater and sludge treatment process, and the overall process removal rate of the WWTP. However, each process's direct measurement is needed to make a true material flow analysis, such as the pumping station, aeration tank, digestion gas, and mixing tank. The results from the Material Flow Analysis showed that the wastewater treatment process can remove nutrients efficiently. The removal rate of TOC, T-N, and T-P were 72%, 62%, 72% respectively. in case of heavy metal, the removal rate of heavy metals was between 62-87%. This means that it can reduce human health risks from heavy metals in treated water.

The mean concentrations of heavy metals in dewatered sludge can be ranked in the following decreasing order: Zn > Cu > Cr > Ni > Pb > As > Mo > Se > Hg > Cd. According to the mean values of HQ, Cu, Zn, and Cr are the top three highest heavy metals that cause non-carcinogen health risks for both children and adults. Heavy metals in dry-based sewage sludge would be toxic for children's health but not for adults. Arsenic was the main heavy metal causing carcinogenic risks. Arsenic and Cadmium did not associate with the carcinogenic risks for children and adults. Comparing the exposure pathway, ingestion was the main pathway for carcinogenic risks, next is dermal contact and inhalation respectively same as the non-carcinogenic health risks.

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