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Occupational Health Risks Associated with Exposure to Particulate Matter; $PM_{2.5}$, PM_{10}, Formaldehyde (HCHO) and other Gases in Wastewater Treatment Plants

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Abstract

Purpose: This research assessed the occupational exposure associated with particulate matter ($PM_{2.5}$ and PM_{10}), formaldehyde vapors (HCHO) and carbon dioxide (CO_2) in a wastewater treatment plant in Nairobi, Kenya. The determined airborne pollutants levels were analyzed to identify potential health risks on the Plant's workers.

Materials and Methods: Air quality measurements were conducted across six locations for a period of three months using a hand-held air quality monitoring device, Temptop M2000 which has high precision formaldehyde, laser particle and carbon dioxide sensors. Three samples were collected at each location and this data analyzed using Statistical software. Observations were also made on the prevalent activities in each location and used in data interpretation.

Findings: $PM_{2.5}$ and PM_{10} levels exceeded WHO guidelines, with the highest concentrations recorded at the pond (11.60±1.57 μg/m³) and inlet works (17.41±1.55 μg/m³), respectively. CO_2 was highest in office areas (571.33±207.1 ppm), while HCHO peaked at the inlet (0.81±0.18 mg/m³), surpassing the 0.08 mg/m³ WHO guideline. Elevated temperatures (mean 27.98±2.36°C) were linked to increase $PM_{2.5}$, while higher relative humidity (mean 44.13±5.75%) correlated with greater concentrations of PM_{10}, HCHO, and CO_2. A one-sample t-test confirmed significantly elevated $PM_{2.5}$ and HCHO levels. The levels for all contaminants were highest during the morning and dropped as the water volumes reduced from in the evening. Hazard quotients indicated substantial health risks, particularly for HCHO at HQ=5.125, suggesting potential respiratory, cardiovascular, and carcinogenic effects. Although the cancer risk from HCHO exposure was found to be minimal, chronic exposure may pose long-term health effects.

Unique Contribution to Theory, Practice and Policy: This study recommended enhanced worker protection through PPE provision, routine medical check-ups, and adherence to national air quality regulations to mitigate risks. Effective hazard management strategies are also crucial for safeguarding health within wastewater treatment environments.

Keywords: *Occupational, Health (I18), Risks exposure (J81), $PM_{2.5}$ (Q53), PM_{10} (Q53), formaldehyde (Q53), wastewater (L95), pollution (Q53)*

1.0 INTRODUCTION

One of the main sources of concern, especially in developing nations like Kenya, is air pollution. According to the United Nations Environment Programme (UNEP, 2021), air pollution poses the largest environmental risk to public health in the world and is thought to be the cause of annual premature deaths of about 7 million people. According to the report, air pollution is to blame for about one third of deaths from stroke, chronic respiratory disease, and lung cancer and one quarter of deaths from heart attacks. The treatment of wastewater has contributed significantly to air pollution originating from biological treatment, chemical dosing and sludge management processes. These emissions include bioaerosols, volatile organic compounds (VOCs), Particulate Matter and heavy metals among others (Viteri et al., 2025). Workers and nearby populations- like the elderly, children and pre-existing medical conditions are highly susceptible to a range of adverse health effects; These include respiratory infections such as asthma, cardiovascular diseases e.g. Heart attacks, neurological disorders or even cancer. Accurately quantifying the level of emissions would therefore strengthen air quality monitoring, create occupational awareness and stimulate the enforcement of environmental regulations.

1.1 Problem Statement

Wastewater treatment processes in Kenya have been accused of exposing workers to toxic chemicals that present various hazards to workers (Oluoch & Ndeda, 2017). A recent study by Yazan and Fatemeh in 2021 revealed that workers in wastewater treatment plants commonly report occupational health symptoms such as stress, anxiety, headaches, dizziness, nausea, and occasional loss of consciousness. This is as a result of the chemical and physical compositions emitted during the water treatment process. Airborne pollutants likely to be emitted during the process include; Particulate Matter ($PM_{2.5}$ & PM_{10}), Sulphur oxides, Methane, Nitrogen oxide, Formaldehyde, Ammonia, Hydro Carbons and Carbon dioxide. These emissions are divided into either direct or indirect (IPCC Report, 2013). Particulate Matter ($PM_{2.5}$ and PM_{10}) is ranked as a criteria pollutant while the National Environmental Management Authority under the chemical management regulations classifies Formaldehyde (HCHO) as a hazardous substance. Most recently, a review conducted by the Health Effect Institute (HEI) reported that exposure to $PM_{2.5}$ and PM_{10} is strongly linked to reduced lung function in children aged 9-14 years in Kenya. Furthermore, poor ventilation, lack of personal protective equipment, and confined working conditions further increase health risks among sanitation workers, particularly in low-resource settings (HEI, 2022; SuSanA, 2021).

2.0 LITERATURE REVIEW

2.1 Exposure to Airborne Pollutants

The Center for Disease Control (2015) and WHO define exposure more specifically as a contact between the individual with the substance either as in gas, solid or liquid over time, so that the intake of a dose may occur through one of the routes of entry through inhalation, skin or eye contact, ingestion, and accidental injection. In wastewater treatment facilities, inhalation serves as a main and effective pathway for exposure since respiratory system is the most prevalent means for gases, vapors, aerosols, mists, fumes, and small particulates to enter the body.

Sharma & Mandal (2023) reported variation in $PM_{2.5}$ elemental composition based on the season in New Delhi, India .Similarly, in Nigeria measured $PM_{2.5}$ levels surpassed the WHO AQI guidelines of 15.3 – 70.2 µg/m3 as a result of vehicle emissions, increased industrialization among other sources (Wambebe et al., 2020). At the Sào Paulo WWTPs, formaldehyde levels in chemical dosing units were at times close to or above 0.9ppm, substantially above OSHA limits (Silva & Mendes, 2019). These parallels underscore the prevalent health risks for the general population and WWTP workers globally highlighting the need for localized empirical exposure assessments in Kenya where published air quality data remains limited.

2.2 Permissible Exposure Limits

The Permissible Exposure Limit for $C0_2$ is set by OSHA at 5,000 parts per million (ppm), or 0.5% CO_2 in the air averaged over 8-hr workday (TWA). Short-term exposure to mild or moderate concentrations of CO_2 through inhalation, below 15,000 ppm, can lead to symptoms such as headaches, drowsiness, and mild respiratory stimulation. At elevated concentrations, CO_2 displaces oxygen in s the air, which can result in suffocation and death if oxygen levels become critically low (SuSanA, 2021).

Particulate Matter could be microscopic and appearing in numerous sizes and chemical composition (U.S EPA, 2019). The World Health Organization (WHO) recommends that annual mean concentrations of particulate matter not exceed 10g/m^3 for $PM_{2.5}$ and 20g/m^3 for PM_{10} respectively, and that daily mass concentrations of $PM_{2.5}$ and PM_{10} should not exceed 25 and 50 g/m^3, respectively. In Kenya, the first schedule of the Environmental management and coordination act (Air Quality regulations, 2022) puts ambient air quality tolerance limit for $PM_{2.5}$ at 75ug/m^3 for 24-hour exposure significantly higher than WHO recommendations . Although PM_{10} is inhalable and is usually deposited in the upper airways (nose, throat, bronchi), $PM_{2.5}$ penetrates deep into the lungs and enters the bloodstream (Pope, 2006). WHO associates $PM_{2.5}$ concentrations to lung cancer, heart attacks, asthma, dementia and low birth weight among newborns (WHO, 2021). PM_{10}, on the other hand, is linked to irritation of the eyes, nose and throat, aggravation of asthma, and reduced lung function among children and the elderly (US E.P.A, 2023).

Formaldehyde (HCHO), a colorless flammable gas with a pungent smell, presents a primary acute exposure hazard of irritation. Although Kenya lacks specific HCHO limits in NEMA regulations, it relies on OSHA permissible exposure limit of 0.75ppm 8-hr time-weighted average (TWA) according to the World Health Organization. Formaldehyde exposure is either through inhalation or dermal absorption, which above 0.1ppm results into respiratory, skin and eye irritation (IARC, 2012). A review conducted by the International Agency for Cancer Research asserted that chronic exposure to HCHO leads to cancer thus carcinogenic.

Previous studies in the Water sector have majorly focused on hazard identification, risk assessment, health and safety management practices. There is gap in terms of empirical data on the levels of airborne hazards with regard to their concentrations and the extent to which workers are exposed to these airborne pollutants.

2.3 Theoretical Framework

This study is grounded in the Hierarchy of Controls theory (NIOSH, 2015), which emphasizes eliminating or reducing workplace hazards through a ranked approach: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE). In this context, administrative controls (e.g., awareness training, monitoring), and PPE (e.g., certified respirators) form the critical lines of defense against airborne pollutant exposure.

Additionally, Environmental Exposure Theory supports the examination of chronic health effects caused by low-dose, long-term exposures common in wastewater environments, reinforcing the need for regular surveillance and policy refinement.

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2.4 Conceptual Framework

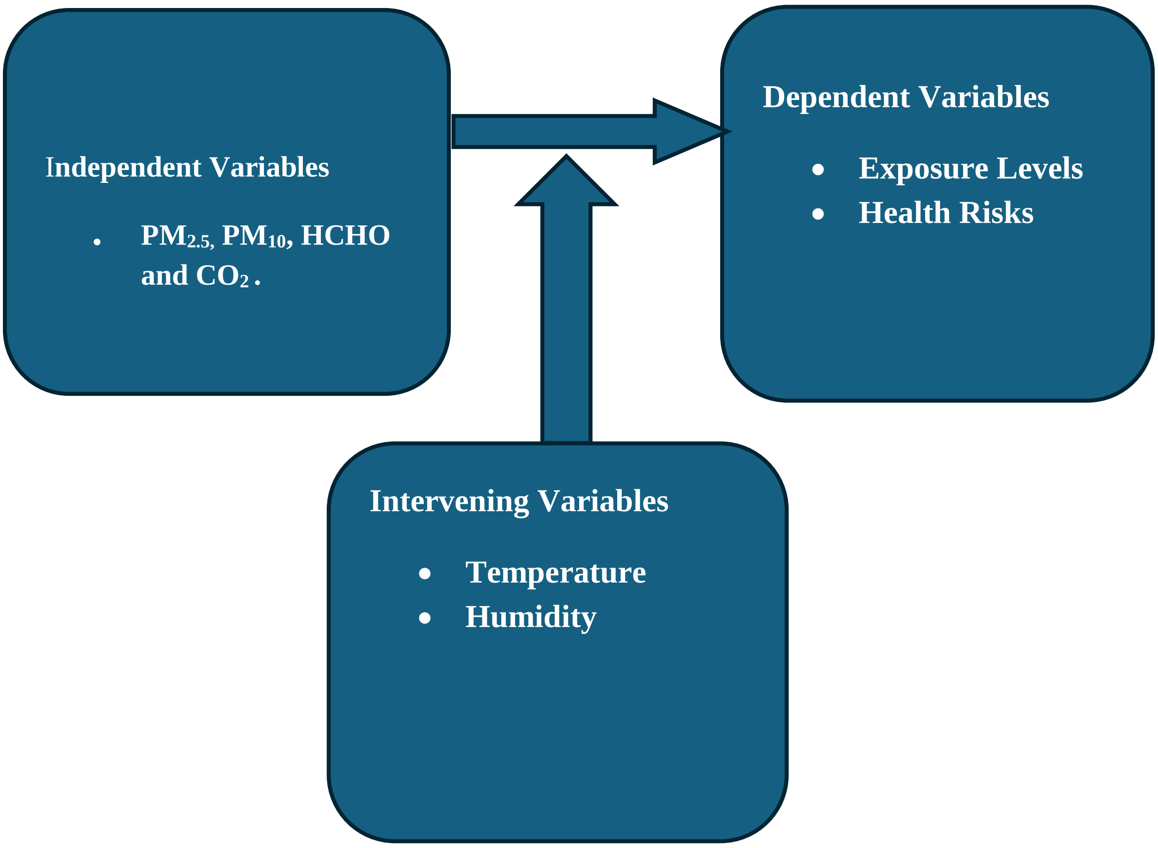

Figure 1: Conceptual Framework Diagram

2.3 Research Gap

Previous studies in the water sector have majorly focused on hazard identification, risk assessment, health and safety management practices. There is gap in terms of empirical data on the levels of airborne hazards with regard to their concentrations and the extent to which workers are exposed to these airborne pollutants. Despite the many emissions from WWTPs, this research selected Particulate matter ($PM_{2.5}$ & PM_{10}) that is regulated as a criterion pollutant by OSHA, EPA and WHO due to its pervasive health burden. In addition, $PM_{2.5}$ has a higher disability-life adjusted year (DALY) burden compared to H_2S (Global Burden of Disease, GBD 2019). Formaldehyde, ranked as Group 1 IARC carcinogen, is also less noticeable at harmful levels (<1ppm) and has increasingly led to unnoticed exposure risks among WWTPs workers. Although CO_2 occurs naturally, it has often been overlooked despite its synergistic effects with other pollutants making it a silent hazard. In addition, PM and HCHO have a lower Occupational exposure prevalence in wastewater treatment plants than H_2S and NO_x. PM has high occupational exposure prevalence in areas like construction and mining while HCHO in manufacturing and healthcare.

Despite regulatory frameworks, Kenya lacks a consolidated occupational exposure database specific to wastewater workers. The Directorate of Occupational Safety and Health Services (DOSHS) under the Ministry of Labour is the lead agency mandated to enforce compliance with Occupational Safety and Health Act (OSHA, 2007), including hazard monitoring and worker protection.

It is therefore important that the toxicity indices for these pollutants in WWTPs be established for context-specific mitigation based on local climate, industrial operations, and regulatory enforcement. This will help safeguard the health and safety of the general population besides the workers considering that these pollutants are airborne

3.0 MATERIALS AND METHODS

3.1 Study Area

This study was conducted at the Dandora Estate Wastewater Treatment Plant (DEWWTP) that is in Kenya and within Nairobi City County and is located 26km from the city. The plant processes domestic and industrial effluent of roughly about 120,000 m^3/day corresponding to nearly 80% of wastewater generated from Nairobi city. It is the main Wastewater Treatment Plant for the Nairobi County with a design capacity of 160,000 m^3.

3.2 Sampling Technique

Sampling locations were determined systematically in order of the wastewater water treatment processes; from the inlet to the final outlet. Three air quality measurements were collected from the five sampling points to increase precision and accuracy.

3.3 Data Collection

Air quality measurements were done using a new generation equipment, Temtop M2000, which has a high precision formaldehyde sensor, laser particle sensor and carbon dioxide sensor. This hand-held device detected these emissions in the atmosphere and converted them into visual data directly. The study had a total of six main sampling locations; the inlet works (coarse screen area), intermediate screen area, office area, primary ponds, final outlet point and a control area located about 20km from the plant. By turning on Temptop M2000, the laser particle sensor was allowed to pre-heat for at least 3minutes before the $PM_{2.5}$, PM_{10}, HCHO and CO_2 interfaces were selected. The real-time concentration values displayed were allowed to run for a period of at least 20 minutes until a relatively steady value was obtained. Data was collected for a period of four days in DEWWTP. This device was calibrated by running it for at least 30 minutes until a zero-point calibration of the sensor was achieved after each measurement. Concentration levels obtained were assumed to be steady for the workers at each location for a period of 8 hours.

3.4 Data Analysis

Data was coded, cleaned, edited and keyed in as per the codes. Statistical Analysis Software (SAS) was then applied and Data presented in figures, charts and tables. The average and standard deviation for each pollutant at every collection site were calculated, and their respective ranges reported. A one-sample t-test for each pollutant was conducted to compare its average concentration at each site to a set standard exposure level. Deviations were considered statistically significant if the p-values were less than 0.05.

4.0 FINDINGS

The results for the six sampling locations were analyzed and represented in tables (1-5) and figures (2& 3) as shown below. To support the evidence of pollution, results from the control area and WHO air quality guidelines (2021) were used in comparison to the wastewater treatment plant locations.

Table 1: Levels of $PM_{2.5}$, PM_{10}, HCHO, CO_2, Temperature and Relative Humidity (RH) at Different Sampling Areas Compared to the WHO Standard.

Location / Pollutant	All Areas within DEWWTP (SD) n=15	INLET POINT (SD) n=3	INTERMEDIATE POINT (SD)n=3	OFFICE AREA (SD) n=3	POND AREA (SD) n=3	FINAL OUTLET (SD) n=3	CONTROL AREA (SD) n=3	WHO 8-hr Standards
$PM_{2.5}$(µg/m^3	10.32±1.14	10.13±1.54	10.33±0.60	9.50±0.54	11.60±1.57	10.03±0.15	5.37±0.49	15
PM_{10}(µg /m^3	16.03±1.90	17.41±1.55	16.64±1.11	15.40±0.86	16.34±2.50	14.35±2.53	9.37±1.94	5
CO_2 (ppm)	462.67±126.28	487.33±92.24	379±20.95	571.33±207.1	506.67±113.02	369±42.72	416±3.61	333
HCHO (mg/m^3)	0.41±0.25	0.81±0.18	0.49±0.11	0.25±0.07	0.22±0.03	0.27±0. 070	0.008±0.004	0.08
Temperature,◦C	27.98±2.36	24.60 ±1.97	27.67±0.06	27.57±0.84	29.1±0.87	30.97±0.86	19.97±0.49	-
RH, %	44.13±5.75	51.3±5.35	45.7±4.07	45.3±2.85	41.27±1.33	37.1±2.66	92.8±0.61	-

Table 2: Pearson's Correlation Coefficient between Temperature, Relative Humidity and the Pollutants

	r-$PM_{2.5}$	r-PM_{10}	r-HCHO	r-CO_2
Temperature	0.1381	-0.4873	-0.6660	-0.2702
Relative humidity	-0.2361	0.3606	0.5916	0.3755

Cohen's guidelines: *0.1-0.29 (Low correlation); 0.29- 0.49 (Moderate correlation); 0.5-1.0 (Strong correlation)*

Summary of findings

4.1 Pollutant Concentrations

According to table 1, all the pollutant levels exceeded the recommended PEL for an 8-hour TWA. Further comparison to the control area proved evidence of pollution within DEWWTP. The continuous oxidation of Nitrogen oxides, Sulphur oxides and certain volatile organic compounds released during the biological treatment of wastewater to form nitrates and sulphates was linked to the highest $PM_{2.5}$ levels observed; 11.60±1.57µg/m^3; at the pond area (Table 1). Chemical reactions of NH_3, NO_2 and SO_2 result into formation of secondary aerosols such as Ammonium Nitrate (NH_4NO_3) and Ammonium Sulphate ($(NH_4)_2SO_4$) which are the major $PM_{2.5}$ components in the atmosphere (Valentina et al., 2020). On the other hand, the inlet area led in the mean concentration of PM_{10}; 17.41±1.55µg/m^3. High turbulence of sewer water at the inlet, movement of exhauster discharge trucks and staff vehicles and the manual unclogging at the coarse screens were some of the activities that facilitated the presence of PM_{10} particles at the area. Other observed human activities within DEWWTP that produced dust included ongoing maintenance works and carting away of solids. Proximity of the office area to a laboratory where water quality tests are conducted was linked to the high CO_2 levels of 571.33±207.1ppm reported. In addition to this, the offices are confined in an area without a sufficient air circulation mechanism and this retains CO_2 for a while. The primary ponds area followed in CO_2 concentration at 506.67±113.02ppm due to the aerobic and anaerobic decomposition of organic matter in wastewater as illustrated by equations 1and 2 below.

COHNS (Organic matter) + O_2+Bacteria ----------------------------------> CO_2+NH_3+ Energy + Other End products (Aerobic)……………………………………….. Equation 1

$C_2H_{12}0_6$ (Glucose) ----------------------------------> $3CO_2$ +$3CH_4$ (Anaerobic)…... Equation 2

Formaldehyde vapors (HCHO) were present at alarming levels with the highest being at the inlet points (0.81±0.18mg/m^3) and decreased gradually towards the final outlet (0.27±0.07mg/m^3). This was an indication that DEWWTP receives wastewater generated from various sources including medical labs, aviation industries, mortuaries and resin production industries that utilize formaldehyde-based adhesives. Similarly, HCHO is formed through secondary reactions such as the photochemical oxidation of methane (Eq. 2), in presence of ultra-violet (UV) rays and a methanotrophic bacteria as shown in equation 3 below (Tucci et al., 2024; Peng et al. 2022).

CH_4+$4O_2$ --------------------> HCHO +H_20+$2O_3$ ……………………………….... Equation 3

Formaldehyde production is also influenced by a variety of factors including, UV light intensity and wavelength, the presence of water and a photo-catalyst (Wei, 2021). Finally, presence of HCHO at the final outlet, where treated wastewater is discharged into Nairobi River, ascertained ineffectiveness in the complete removal or subsidization of this pollutant towards the PEL before release into the environment. Repeated exposure of workers in DEWWTP to HCHO overtime may lead to the development of cancerous cells such as leukemia, brain cancer, pancreatic cancer and ocular melanoma (Marsh et al., 2016).

4.2 Correlation between the Pollutants, Temperature and Relative Humidity

Temperature in the wastewater treatment process affects the activity rate of bacteria and the subsequent rate of oxygen adsorption (Ramalho, 2013). From observation, the possible sources of relative humidity (RH) within DEWWTP could be evaporation from open maturation ponds, splashing from mixing processes and sludge dewatering. In order to determine how temperature and relative humidity affect pollutant concentration, Pearson's correlation coefficient, r, was used. The strength of these relationships was interpreted using Cohen's; 1988; guidelines (table 2).

According to table 3 above, temperature exhibited a moderate negative correlation with PM_{10} (r= -0.4873) since increased convection facilitates atmospheric dispersion/ deposition of coarse particles. And a weak positive relationship with $PM_{2.5}$ (r=0.1381) an indication of little significance in secondary aerosol formation as discussed earlier. CO_2 exhibited a weak negative correlation (r= -0.2702) with temperature. However, the correlation between temperature and formaldehyde was quite significant (r=-0.666) A graphical analysis indicated that as the air temperature increased HCHO levels dropped significantly (Fig. 2). High temperatures decrease the air density which in turn enhances natural convection and ventilation in open areas at WWTPs. This leads to more efficient dispersion of airborne HCHO thus reducing localised concentrations (Widiana et al., 2013). The correlation suggested that HCHO could also be emanating from other sources such as decomposition of biomass and wall paintings from buildings (Srinandini et al., 2011).

Relative humidity reported a moderate positive correlation with CO_2 (r=0.3755) and a strong correlation with HCHO (r=0.5916) respectively. According to Jacob and Winner, an r-value of 0.3606 (RH/PM_{10}) could be as a result of increased coarse particle mass through condensation from wet surfaces (Jacob et al., 2009). A graphical representation (Fig.3), of the RH/HCHO correlation, indicated that high relative humidity favoured an increase in formaldehyde levels as a result of minimal photodegradation under humid or cloudy conditions (Srinandini et al., 2011).

In the formulation of the research, it was hypothesized that the pollutant levels in the different areas at the Dandora Wastewater treatment plant do not significantly exceed the standard maximum levels. The results of a one sample t-test comparing the determined pollutant levels to the standard maximum are shown in table 3 below. It emerged that the $PM_{2.5}$ and HCHO exposure levels at all locations were significantly higher as indicated by p-vales of <0.05. In this regard, the null hypothesis that pollutant levels in the different areas at the DEWWTP significantly exceed the standard maximum levels was accepted for $PM_{2.5}$ and HCHO and rejected for CO_2 and PM_{10}.

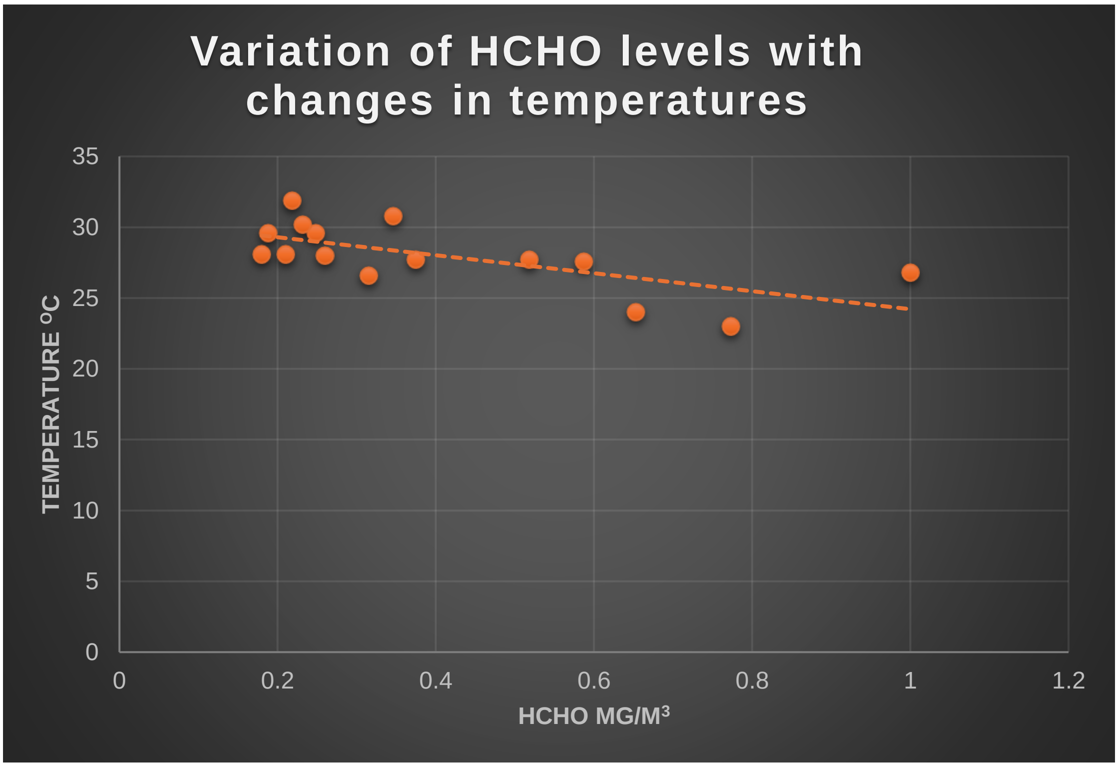

Figure 2: A Graph Showing the Variation in HCHO Levels with Changes in Air Temperature at DEWWTP.

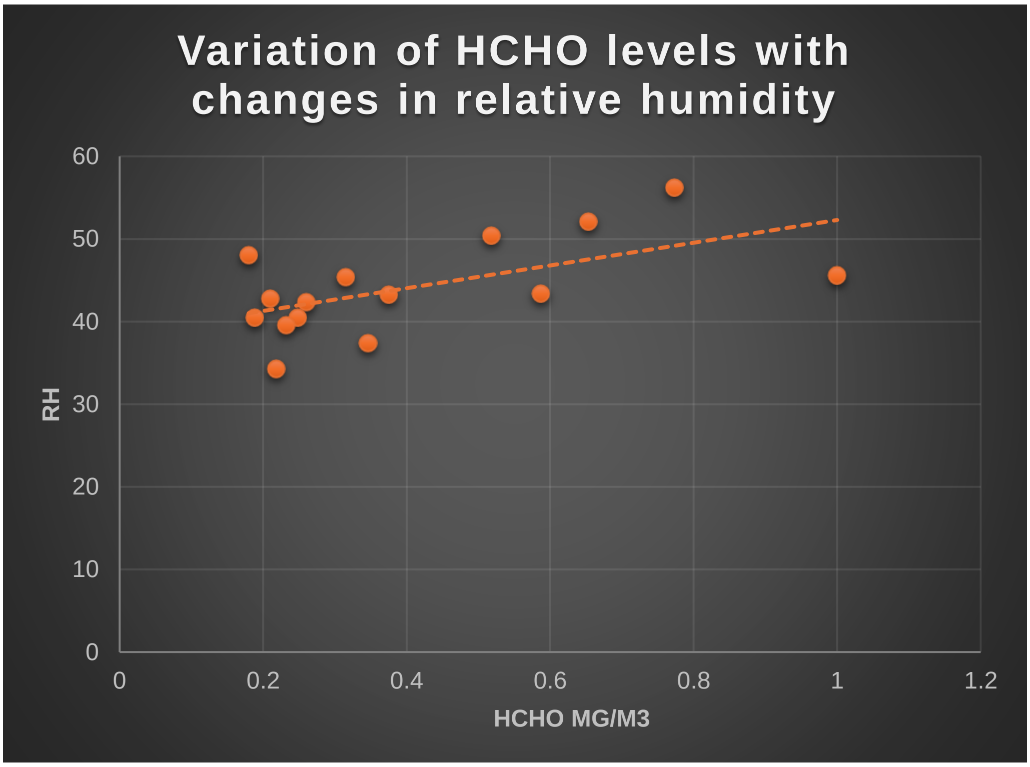

Figure 3: A Graphical Representation of the Variation in HCHO Levels with Changes in RH Levels

Table 3: P-values of a One-Sample t-test Conducted for the Six Sampling Locations

Location	Pollutant	t-value	WHO Standard	P-value (0.05)	Significance
INLET	$PM_{2.5}$	5.789	5	0.0286	Significant
	PM_{10}	2.684	15	0.1153	**Non-significant**
	HCHO	7.162	0.08	0.0189	Significant
	CO_2	2.898	333	0.1013	**Non-significant**
INTERMEDIATE	$PM_{2.5}$	15.516	5	0.0041	Significant
	PM_{10}	2.564	15	0.1243	**Non-significant**
	HCHO	6.621	0.08	0.0221	Significant
	CO_2	3.803	333	0.0627	**Non-Significant**
OFFICE	$PM_{2.5}$	14.378	5	0.0048	Significant
	PM_{10}	0.811	15	0.5028	**Non-significant**
	HCHO	4.380	0.08	0.0484	Significant
	CO_2	1.993	333	0.1844	**Non-significant**
POND	$PM_{2.5}$	7.290	5	0.0183	Significant
	PM_{10}	0.930	15	0.4506	**Non-significant**
	HCHO	7.723	0.08	0.0164	Significant
	CO_2	2.661	333	0.1169	**Non-significant**
FINAL OUTLET	$PM_{2.5}$	57.073	5	0.0003	Significant
	PM_{10}	-0.442	15	0.7015	**Non-significant**
	HCHO	4.572	0.08	0.0447	Significant
	CO_2	1.460	333	0.2818	**Non-significant**
	$PM_{2.5}$	1.29	5	0.327	**Non-significant**

CONTROL POINT	PM_{10}	-5.02	15	0.037	**Significant**
	HCHO	-28.61	0.08	0.0012	**Significant**
	CO_2	39.87	333	0.0006	**Significant**

Table 4: Hazard Quotients Calculated Using the Determined Exposure Concentration, EPC.

Pollutant	EPC	WHO Standards	Hazard Quotient	Health Risks
$PM_{2.5}$	10.32μg/m^3	5μg/m^3	2.064	Respiratory and cardiovascular issues, aggravation of existing heart or lung diseases
PM_{10}	16.03μg/m^3	15μg/m^3	1.069	Respiratory and cardiovascular issues, aggravation of existing heart or lung diseases
HCHO	0.41mg/m^3	0.08mg/m^3	5.125	Irritation of the eyes, nose and throat, Cancer risk, Skin allergies
CO_2	462.67ppm	333ppm	1.389	No direct health effect at observed frequency level

Based on table 4 results, HCHO and $PM_{2.5}$ are the leading in potential health hazards with HQs of 4.988 and 2.064 respectively. CO_2 and PM_{10} followed with HQs of 1.389 and 1.069respectively. A hazard quotient equal to or less than one indicates no probable health effects expected. HQ values greater than one indicate potential adverse health outcomes on DEWWTP workers.

The common route of exposure of the above pollutants is inhalation apart from HCHO that occurs in gaseous and liquid form. Previous research suggests that acute and chronic exposure to $PM_{2.5}$ increases the likelihood of cardiovascular disease such as hypertension (Chayakrit et al., 2023). A publication by the California Air Resources Board (CARB) reported that PM_{10} particles can still be inhaled in the upper parts of the lungs leading to coughing, wheezing and aggravation of existing diseases such as asthma. Despite CO_2 having a HQ>1, there are no direct health effects associated with the determined frequency levels of 400 to 500ppm (Jacobson et al. 2019).

A HQ of 5.125 is an indication that workers in the wastewater treatment plant workers are at a very high risk of severe health consequences in the long run from formaldehyde vapors. According to the U.S EPA Integrated Risk Information Systems (IRIS, 2024) several studies have shown that acute exposure to HCHO causes irritation of the eyes, nose, and throat. A reference concentration RfC of 0.0007mg/m^3 has been set by IRIS as a threshold for non-carcinogenic effects. Exposures exceeding this levels are associated with an increased risk of adverse health outcomes including respiratory conditions such as asthma, neurotoxicity leading to brain cancer, reproductive and developmental thereby asserting the findings of (Lei et al., 2017).

The authority provides non-cancer above which HCHO results into adverse cancerous effects such as asthma, brain cancer, reproductive and developmental toxicity on humans.

To assess the cancer risk due to chronic exposure for full-time staffs at DEWWTP, it was assumed that they work for at least 8.5hr/day (8.5hr/24hrs), 6days/wk (6days/7days), 47 weeks/yr (47weeks/52.14weeks) and for 20yrs (RME) with an average life expectancy of 78yrs in line with U. S Agency for Toxic Substances and Disease Registry (ATDSR, 2020) guidelines. The DEWWTP workers' exposure factor (EF) is determined;

$$EF_{chronic} = \frac{8.5 \times 6 \times 47 \times 20}{24 \times 7 \times 52.14 \times 78} = 0.07$$ ………………………………………….… **Equation 4**

Using the globally recognized formaldehyde Inhalation Unit Risk (IUR) of 1.1×10^-5 µg/m^3, the cancer risk assessment is calculated as shown below (Eq. 5).

$$Cancer\ Risk = IUR \times EPC \times EF$$ ……………………………………………..… **Equation 5**

$$Cancer\ Risk\ DEWWTP\ Workers = 1.1 \times 10^{-5} \times 4.1 \times 10^{-4} \times 0.07 = 3.16 \times 10^{-10}$$ ……………………………………………………………………...… **Equation 6**

The result suggests that out of 1billion workers exposed only about 0.316 (or approximately 1 in 3billion) might develop cancer as a result which is considered a very small (extremely low) risk since it is way below the globally acceptable risk of 1.0 ×10^{-6}. [24]

Nevertheless, considering pollutant concentrations against the control area and WHO guidelines, there's an urgent need of an effective hazard management plan at DEWWTP such as provision of PPEs, occupational health and safety trainings while conducting frequent medical check-ups among the workers. This plan should align with the relevant legal framework in Kenya such as Particulate Matter regulations and the Environmental Management and Co-ordination regulations (2013) on air quality.

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study established that $PM_{2.5}$ and HCHO are the leading air pollutants in DEWWTP with 8-hour mean concentrations of 10.32±1.14ug/m^3 and 0.41±0.25mg/m^3 respectively. Despite minimal human activities being observed at the pond and final outlet areas, more emphasis should be put on workers at inlet, intermediate screens and offices where these pollutants are high. Given the 8-hour mean recorded levels of $PM_{2.5}$ and a HQ>1 exceeding the USEPA acceptable risk threshold, assuming a 20 years exposure period, workers are at a moderate-to-high risk of cardiovascular and respiratory diseases, including lung cancer and stroke (WHO,2021). The continuous movement of wastewater discharge trucks in and out of the premises contributes significantly to high PM10 levels at the inlet location. This calls for more protection mechanisms such as the N95 respirator or goggles for staffs around this area. However, the cancer risk calculated under current exposure scenarios remains below the EPA's acceptable risk threshold of 1 in 1,000,000, indicating a negligible cancer risk. CO2 remained well within OSHA's permissible exposure limit of 5000ppm ruling out the possibility of any potential health threat. High humidity slows photolysis of HCHO, while elevated temperature increases convective dispersion - reducing accumulation.

5.2 Recommendations

Employees within the WWTP should be trained either annually or quarterly through interactive workshops, site demonstrations or digital modules on potential hazards, PPE use and emergency response through accredited Department of Occupational Safety and Health Services (DOSHS) personnel. Those working with at the inlet, intermediate and office areas, where pollutant levels were above average, should receive N95 respirators for PM protection and P100 or ABEK1 cartridges for chemical vapors such as formaldehyde. This would ensure that the risk of exposure to the pollutants is significantly reduced thus lowering the risk of health problems among them. Annual health checkups such as pulmonary function tests (Spirometry), formaldehyde bio-monitoring, dermal and ocular examination. This would enhance the detection of exposure-related diseases and reduce the risk of existing disease aggravation among workers. To ensure compliance, NEMA should continuously monitor the ambient air quality within and around WWTP. Consequently, Ministry of Labour and Social Protection in conjunction with DOSHS should oversee workers' training while conducting workplace safety audits. Finally, future researchers should encompass a wider range of pollutants while evaluating how weather and climatic conditions of an area influence their dynamics.

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Conflict of Interest Declaration

None

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