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Preliminary microbiological and trace-metal screening of wastewater exposed to diesel exhaust in a mobile gas-liquid system

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ABSTRACT

Domestic wastewater stored in non-sewered sanitation systems may retain microbiological hazards throughout collection and transport. This study presents a preliminary assessment of a mobile gas-liquid system in which diesel engine exhaust was introduced into domestic wastewater through a diffuser assembly installed in a sanitation tank. The objective was to evaluate changes in the qualitative detectability of *Salmonella* spp. and intestinal parasite eggs and to screen selected trace metals in wastewater and soil. Two independent laboratory series were considered. In the first series, *Salmonella* was isolated from untreated wastewater and from wastewater exposed to exhaust for 15 min, whereas it was not isolated after 30 and 60 min. In the second series, *Salmonella* was present in wastewater collected directly from the treatment plant and after contact with the sanitation tank but was not detected after 30, 60, or 90 min of exhaust exposure. Eggs of *Ascaris* spp., *Trichuris* spp., and *Toxocara* spp. were not detected in any wastewater variant. Concentrations of Pb, Cd, Cu, Zn, Ni, and Hg were determined in the second series. Contact with the sanitation tank was accompanied by increases in several metals, particularly Cu and Zn, but no consistent exposure-time-dependent increase was observed between 30 and 90 min. Soil receiving the exposed wastewater was additionally screened for Cd, Cu, Ni, Pb, Zn, Hg, Cr, parasite eggs, and *Salmonella*. No systematic increase in trace-metal content with wastewater exposure time was identified. The results demonstrate a reproducible qualitative transition in *Salmonella* detectability between 15 and 30 min under the tested conditions. However, the absence of microbial enumeration, experimental replication, exhaust characterization, and analysis of organic exhaust-derived contaminants limits the findings to preliminary screening rather than validation of a sanitation technology.

Keywords: domestic wastewater, diesel exhaust, gas-liquid contact, *Salmonella*, trace metals, sanitation tank, soil screening.

INTRODUCTION

Safe management of domestic wastewater remains a challenge in rural, peri-urban, and otherwise non-sewered areas. Although decentralized treatment systems are increasingly available, storage tanks and periodic wastewater transport continue to be used where connection to a sewer network or installation of an on-site treatment plant is technically, economically, or organisationally constrained. Wastewater retained in such systems may contain pathogenic microorganisms and may preserve its sanitary risk during storage, pumping, and transport (Massoud et al., 2009; Capodaglio, 2017).

The safe handling or reuse of wastewater requires simultaneous consideration of microbiological and chemical hazards. Microorganisms of faecal origin, including pathogenic bacteria and intestinal parasites, may pose direct risks to operators, soil, crops, surface water, and groundwater. At the same time, a process intended to reduce microbial risk should not introduce chemicals that create a different or more persistent environmental hazard. Risk-based wastewater management therefore requires assessment of both pathogen occurrence and selected chemical indicators rather than consideration of microbiological effects alone (World Health Organization, 2006; Capodaglio, 2017).

Transport of wastewater by a sanitation vehicle is normally a passive logistical operation. The vehicle engine generates a continuous stream of hot exhaust gas, while the sanitation tank contains a liquid medium that may remain in the vehicle for several tens of minutes. Connecting these two streams creates the possibility of using transport time as a gas-liquid contact interval. Introducing gas through submerged diffusers may promote mixing, gas dissolution, heat transfer, and local physicochemical changes within the liquid. Micro- and fine-bubble systems are used in water and wastewater treatment because a large interfacial area and prolonged gas-liquid contact can enhance mass transfer and mixing (Agarwal et al., 2011; Temesgen et al., 2017). More recent reviews have also identified micro- and nanobubble processes as potentially useful components of wastewater treatment systems, although their effectiveness depends strongly on gas composition, bubble size, hydraulic conditions, and target contaminants (Mohd Selihin and Tay, 2022; Shen et al., 2022).

Diesel exhaust is not, however, an inert treatment gas. It is a complex mixture containing carbon dioxide, carbon monoxide, nitrogen oxides, hydrocarbons, aldehydes, particulate matter, and other combustion-related constituents. Diesel particles may carry polycyclic aromatic hydrocarbons and trace elements derived from fuel, lubricating oil, engine wear, and exhaust-system components. Therefore, direct contact between diesel exhaust and wastewater creates both a potential microbial-inactivation mechanism and a potential pathway for secondary chemical contamination (United States Environmental Protection Agency, 2002; Liang et al., 2005).

The technical concept evaluated in this study originated from a mobile system in which diesel exhaust is distributed through domestic wastewater in a sanitation tank by means of submerged diffusers. The constructional basis of the system was subsequently protected by Polish Patent PL 235193 B1 (Durczak et al., 2020). Previous laboratory reports related to the system contained qualitative microbiological results, but the complete dataset also included determinations of selected trace metals in wastewater and in soil receiving the exposed wastewater. These results have not previously been integrated into a single environmental assessment.

The objective of the present study was to perform a preliminary microbiological and trace-metal screening of domestic wastewater exposed to diesel exhaust in a mobile gas-liquid system. The specific aims were to compare the qualitative presence of *Salmonella* spp. in wastewater before and after different exhaust-exposure times, assess the occurrence of viable intestinal parasite eggs, compare selected trace-metal concentrations in wastewater collected before tank contact, after tank contact, and after 30–90 min of exhaust exposure, screen selected trace metals and sanitary indicators in soil following application of the exposed wastewater, and identify the evidential limitations and environmental uncertainties associated with the available dataset.

MATERIALS AND METHODS

Mobile gas-liquid system

The investigated system was based on a sanitation tank connected to the exhaust system of a diesel engine. A controlled portion of the exhaust stream was redirected through a gas conduit into a distribution pipe installed inside the tank. Diffuser elements located near the bottom of the tank dispersed the exhaust gas into the wastewater. The installation also included a control valve, pressure gauge, and safety valve.

The submerged diffuser arrangement was intended to increase the gas-liquid interfacial area and induce liquid circulation. Wastewater samples were collected from an outlet or sampling point associated with the sanitation tank after defined gas-contact times. The arrangement of the mobile gas-liquid system is shown in Figure 1.

The system was evaluated as a preliminary engineering concept. The available documentation did not contain sufficiently complete records of exhaust-gas flow rate, engine load, exhaust temperature, wastewater temperature, pressure variation, bubble-size distribution, diffuser pore size, or gas composition. These parameters were therefore not reconstructed retrospectively and were not used as quantitative process variables.

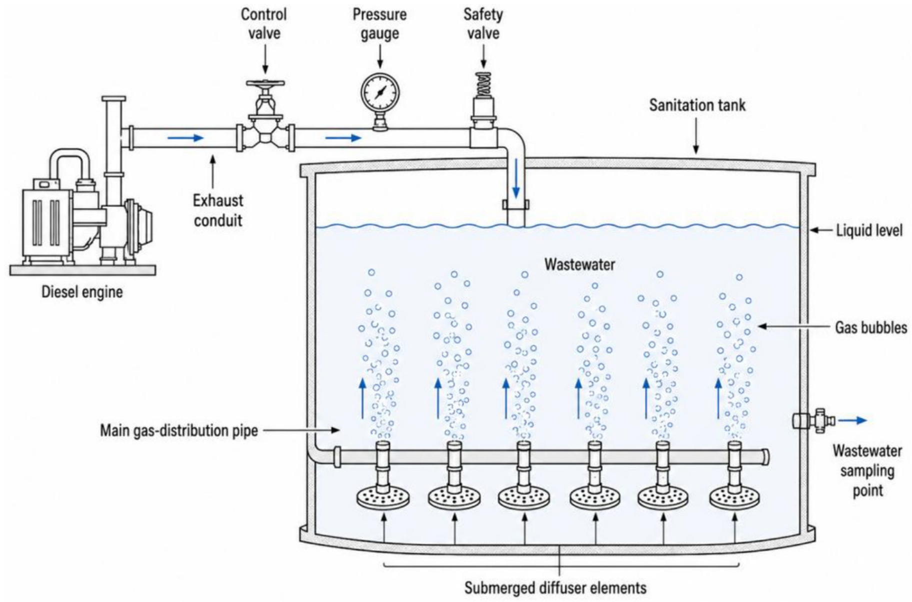

Figure 1. Schematic diagram of the mobile gas-liquid system used for diesel-exhaust exposure of domestic wastewater

Experimental design

The study was based on two independent laboratory investigation series performed during an earlier stage of experimental development of the system. The series were analysed by external accredited laboratories. The first independent laboratory series included domestic wastewater samples collected after 0, 15, 30, and 60 min of exhaust contact. The samples were examined for the presence of bacteria of the genus *Salmonella* and for viable intestinal parasite eggs. The 0-min sample represented untreated wastewater, while the subsequent samples represented increasing gas-liquid exposure times. The analyses were performed by Aquanet Laboratorium Sp. z o.o., an accredited laboratory. Detection of *Salmonella* was performed using laboratory procedure PB/PBO-7, based on the reference method PN-Z-19000-1:2001. Viable intestinal parasite eggs were determined using procedure PB/PBO-8.

The second independent laboratory series included five wastewater conditions: wastewater collected directly from the wastewater treatment plant, wastewater after contact with the sanitation tank but before the defined exhaust-exposure interval, and wastewater after 30, 60, and 90 min of diesel-exhaust exposure. The first condition was used as the source-wastewater control. The second condition was used as the tank-contact control and was intended to distinguish changes associated with contact with the sanitation vehicle from changes occurring during prolonged exhaust bubbling. Each wastewater sample was analysed for Pb, Cd, Cu, Zn, Ni, Hg, eggs of *Ascaris* spp., *Trichuris* spp., and *Toxocara* spp., and the presence of *Salmonella* spp. The samples were single samples representing individual process conditions.

A parallel soil-screening series included soil without wastewater application and soil receiving wastewater exposed to exhaust for 30, 60, or 90 min. The soil was analysed directly after wastewater application. Additional samples corresponding to the 30-, 60-, and 90-min wastewater variants were collected and analysed six days after application. The soil samples were examined for Cd, Cu, Ni, Pb, Zn, Hg, Cr, eggs of *Ascaris* spp., *Trichuris* spp., and *Toxocara* spp., and *Salmonella* spp. The soil analyses were intended as a short-term screening of possible changes after wastewater application. They were not designed as a replicated field experiment or as a long-term environmental fate study.

Laboratory methods and data treatment

The wastewater and soil samples from the second laboratory series were analysed by SGS Polska Sp. z o.o., Environmental Laboratory, using accredited or laboratory-standard procedures. Pb, Cd, Cu, Zn, Ni, and Cr were determined using inductively coupled plasma optical emission spectrometry according to PN-EN ISO 11885:2009 and the associated SGS laboratory procedure KJ-I-5.4-174. Hg was determined according to PN-EN 1483:2007 and laboratory procedure KJ-I-5.4-35. Intestinal parasite eggs in water and wastewater were determined using SGS procedure KJ-I-5.4-53M. Detection of *Salmonella* spp. was conducted according to PN-EN ISO 6579:2003, using 25 g of sample.

For values preceded by the symbol <, the result was below the lower limit of quantification of the applied analytical method. These values were retained as censored results and were not replaced with zero. Metal concentrations in wastewater were reported in mg/L, while metal concentrations in soil were reported in mg/kg dry matter. The available material consisted of single accredited laboratory determinations for individual experimental variants. No independent biological or technical replicates were available, and the wastewater and soil samples were collected by the commissioning party rather than by the analytical laboratory. Consequently, the laboratory reports confirmed analytical quality but did not independently verify sampling representativeness, and inferential statistical analysis was not performed.

The results were evaluated descriptively by comparing qualitative presence or absence of *Salmonella*, the occurrence of parasite eggs, trace-metal concentrations between controls and exhaust-exposure times, whether metal concentrations showed a consistent monotonic relationship with exposure time, and soil-screening results between the control and wastewater-amended samples. These descriptive comparisons do not establish statistical significance, microbial inactivation kinetics, causal mechanisms, or environmental compliance.

RESULTS

Microbiological screening in the first laboratory series

The results of the first microbiological screening series are presented in Table 1.

The untreated sample and the sample exposed for 15 min were positive for *Salmonella*. In contrast, *Salmonella* was not isolated from the samples exposed for 30 or 60 min. The qualitative transition therefore occurred between 15 and 30 min under the conditions of this test series.

Viable intestinal parasite eggs were not isolated in any sample. Because the control was also negative, the parasite-egg results did not demonstrate an effect of diesel-exhaust exposure.

Microbiological and trace-metal screening of wastewater

The complete wastewater-screening results from the second laboratory series are presented in Table 2.

Salmonella was present in wastewater collected directly from the treatment plant and remained present after contact with the sanitation tank. It was not detected after 30, 60, or 90 min of exhaust exposure. This result was consistent with the first laboratory series, in which the qualitative transition occurred between 15 and 30 min.

No intestinal parasite eggs were found in any wastewater condition. As in the first laboratory series, the absence of eggs in the untreated control prevented attribution of this result to the investigated process.

The trace-metal results showed that several concentrations differed between the source wastewater and the tank-contact control. Pb increased from 0.0054 to 0.010 mg/L, Cu from 0.020 to 0.11 mg/L, Zn from 0.089 to 2.38 mg/L, and Ni from below 0.005 to 0.013 mg/L after contact with the sanitation tank.

During the subsequent exhaust-exposure period, Pb remained within a narrow range of 0.013-0.014 mg/L. Cu increased from 0.17 mg/L after 30 min to 0.30 mg/L after 60 min and remained at 0.30 mg/L after 90 min. Zn decreased from 2.30 mg/L after 30 min to 1.79 and 1.78 mg/L after 60 and 90 min, respectively. Ni varied from 0.014 to 0.019 mg/L.

Table 1. Qualitative microbiological results for wastewater exposed to diesel exhaust in the first laboratory series

Exhaust-exposure time, min	Salmonella result	Viable intestinal parasite eggs
0	Isolated	Not isolated
15	Isolated	Not isolated
30	Not isolated	Not isolated
60	Not isolated	Not isolated

Table 2. Microbiological indicators and trace-metal concentrations in wastewater before and after diesel-exhaust exposure

Parameter	Treatment-plant wastewater	Tank-contact control	30 min	60 min	90 min
Pb, mg/L	0.0054	0.010	0.013	0.014	0.013
Cd, mg/L	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025
Cu, mg/L	0.020	0.11	0.17	0.30	0.30
Zn, mg/L	0.089	2.38	2.30	1.79	1.78
Ni, mg/L	<0.005	0.013	0.014	0.014	0.019
Hg, mg/L	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Ascaris, *Trichuris*, and *Toxocara eggs*, number/L	0	0	0	0	0
Salmonella spp.	Present	Present	Not detected	Not detected	Not detected

Note: Values preceded by < were below the lower limit of quantification of the applied method.

Cd and Hg remained below their respective limits of quantification in all wastewater samples. The results therefore did not show a consistent monotonic increase in all measured metals with increasing exhaust-exposure time. Nevertheless, the substantial differences between the source wastewater and the tank-contact control indicated that contact with the tank and its associated components was itself an important potential source of changes in wastewater composition.

Soil screening directly after wastewater application

The soil results obtained directly after wastewater application are presented in Table 3.

Cd ranged from 1.12 to 1.32 mg/kg dry matter, and Cu ranged from 2.91 to 3.24 mg/kg dry matter. Pb varied between 11.0 and 12.1 mg/kg dry matter. These ranges did not display a systematic increase with the exhaust-exposure time applied to the wastewater.

Ni and Cr were below 2.5 mg/kg dry matter in all soil samples. Zn was 3.1 mg/kg dry matter in the untreated soil and below 2.5 mg/kg dry matter in all wastewater-amended samples. Hg values were low and variable, with no monotonic relationship to exposure time.

Neither *Salmonella* nor intestinal parasite eggs were detected in the soil control or in the wastewater-amended soil samples.

Soil screening six days after wastewater application

The soil results obtained six days after application are presented in Table 4.

Six days after application, Cd, Cu, and Ni were below their respective limits of quantification in all variants. Pb ranged from 9.64 to 10.1 mg/kg dry

Table 3. Trace-metal concentrations and sanitary indicators in soil directly after wastewater application

Parameter	Soil without wastewater	Wastewater exposed for 30 min	Wastewater exposed for 60 min	Wastewater exposed for 90 min
Cd, mg/kg d.m.	1.12	1.23	1.32	1.14
Cu, mg/kg d.m.	3.04	3.24	3.01	2.91
Ni, mg/kg d.m.	<2.5	<2.5	<2.5	<2.5
Pb, mg/kg d.m.	12.1	11.0	11.3	11.6
Zn, mg/kg d.m.	3.1	<2.5	<2.5	<2.5
Hg, mg/kg d.m.	0.015	0.0091	0.016	<0.005
Cr, mg/kg d.m.	<2.5	<2.5	<2.5	<2.5
Ascaris, *Trichuris*, and *Toxocara eggs*, number/kg d.m.	0	0	0	0
Salmonella spp.	Not detected	Not detected	Not detected	Not detected

Note: d.m. – dry matter. Values preceded by < were below the lower limit of quantification.

Table 4. Trace-metal concentrations and sanitary indicators in soil six days after application of wastewater exposed to diesel exhaust

Parameter	Wastewater exposed for 30 min	Wastewater exposed for 60 min	Wastewater exposed for 90 min
Cd, mg/kg d.m.	<0.25	<0.25	<0.25
Cu, mg/kg d.m.	<2.5	<2.5	<2.5
Ni, mg/kg d.m.	<2.5	<2.5	<2.5
Pb, mg/kg d.m.	10.1	9.96	9.64
Zn, mg/kg d.m.	14.3	<2.5	<2.5
Hg, mg/kg d.m.	0.0076	0.0089	0.0052
Cr, mg/kg d.m.	2.62	<2.5	2.95
Ascaris, *Trichuris*, and *Toxocara eggs*, number/kg d.m.	0	0	0
Salmonella spp.	Not detected	Not detected	Not detected

Note: d.m. – dry matter. Values preceded by < were below the lower limit of quantification.

matter, while Hg ranged from 0.0052 to 0.0089 mg/kg dry matter.

The Zn concentration of 14.3 mg/kg dry matter in the 30-min variant differed from the values below 2.5 mg/kg dry matter in the 60- and 90-min variants. Cr was quantified in the 30- and 90-min variants but remained below 2.5 mg/kg dry matter in the 60-min variant. Because the experiment did not include replicate soil samples and soil is spatially heterogeneous, these differences could not be attributed confidently to wastewater exposure time.

No *Salmonella* or intestinal parasite eggs were detected in any of the soil samples analysed after six days.

DISCUSSION

Qualitative change in *Salmonella* detectability

The two independent laboratory series produced a similar qualitative result. In the first series, *Salmonella* was isolated at 0 and 15 min but not after 30 or 60 min. In the second series, *Salmonella* was present in both control conditions but was not detected after 30, 60, or 90 min. The agreement between these series supports the observation that a change in detectability occurred during the first 30 min of gas-liquid contact under the investigated conditions.

The observed transition is consistent with the broader principle that wastewater safety must be assessed through pathogen reduction rather than through the presence of a treatment device alone. WHO guidance emphasizes health-based targets and risk management in wastewater use, including microbial safety as a central component (World Health Organization, 2006). However, the categorical presence-absence result obtained here should not be interpreted as proof of complete microbial inactivation. It does not indicate the initial concentration of viable organisms, the magnitude of reduction, or the probability of survival below the analytical detection threshold. The result also does not distinguish between irreversible inactivation, sublethal injury, temporary non-culturability, or analytical variability.

A validated wastewater-disinfection study would normally include quantitative microbial enumeration, replicate experiments, defined detection limits, and calculation of log-reduction values. Such information was not available in the present dataset. Therefore, the current findings are more appropriately described as a reproducible qualitative screening signal than as microbial kinetic evidence.

The transition between 15 and 30 min may have resulted from several simultaneous processes. Exhaust bubbling could have increased the wastewater temperature, promoted intensive mixing, altered dissolved-gas concentrations, reduced pH through carbon-dioxide dissolution, or introduced reactive combustion products. Fine bubbles can increase interfacial area and gas-transfer efficiency compared with larger bubbles, and this general mechanism has been discussed for water and wastewater treatment applications (Agarwal et al., 2011; Temesgen et al., 2017). Nevertheless, the available records did not include temperature, pH, dissolved oxygen, oxidation-reduction potential, or exhaust composition. The relative contribution of thermal, mechanical, and chemical effects therefore remains unresolved.

Parasite-egg results

No viable intestinal parasite eggs were detected in any wastewater or soil sample. This finding cannot be interpreted as evidence that diesel-exhaust exposure inactivated parasite eggs because they were also absent from the untreated controls. This interpretation is important because helminth eggs are commonly treated as robust sanitary indicators in wastewater reuse and agricultural exposure assessments (World Health Organization, 2006).

The result is nevertheless relevant to description of the tested material. It demonstrates that the wastewater used in the investigated series did not contain detectable eggs of *Ascaris*, *Trichuris*, or *Toxocara* under the applied analytical procedures. The dataset therefore provides no basis for assessing the effectiveness of the system against helminth eggs. A negative result after treatment has evidential value only when the target organism or indicator was present in an appropriate control or introduced at a known concentration.

Trace metals in wastewater

The trace-metal data provide a partial response to concerns regarding transfer of inorganic contaminants from the engine, exhaust line, sanitation tank, or associated fittings into the wastewater. Diesel emissions and combustion-related particles may contain inorganic and organic components, including metallic traces associated with fuel, oil, engine wear, and exhaust-system materials (United States Environmental Protection Agency, 2002; Liang et al., 2005).

The most pronounced changes occurred between the wastewater-treatment-plant sample and the tank-contact control. Cu increased by more than fivefold and Zn by more than twentyfold before the defined 30-min exhaust-exposure period. Pb and Ni also increased. These observations indicate that the sanitation tank, previous residues, metal components, pipework, fittings, or the initial contact with the exhaust system may have affected wastewater composition.

The tank-contact control was therefore essential. Without this sample, the increase in metals relative to the treatment-plant wastewater could have been attributed entirely to prolonged exhaust bubbling. Instead, the results show that a major part of the difference was already present immediately after tank contact. Between 30 and 90 min, the metals did not follow a common time-dependent pattern. Pb was essentially stable, Zn decreased with exposure time, Cu increased between 30 and 60 min and then remained unchanged, Ni showed only a small increase at 90 min, and Cd and Hg remained below the limits of quantification.

This pattern does not support a simple interpretation in which longer exhaust exposure caused progressive accumulation of every measured metal. It also does not demonstrate the absence of contamination. Single samples cannot distinguish genuine process changes from temporal variability, heterogeneity of wastewater, analytical uncertainty, or release of residues from the installation. The measured metals also represent only a limited fraction of possible exhaust-derived contaminants. Diesel exhaust may contain particulate carbon, organic compounds, aldehydes, polycyclic aromatic hydrocarbons, and nitrogen- and sulfur-containing reaction products. Particle-bound PAHs and diverse organic compounds have been identified in diesel emissions, while exhaust composition depends on engine technology, fuel, load, maintenance, and after-treatment efficiency (Liang et al., 2005; Kostenidou et al., 2021). The present data therefore cannot establish comprehensive chemical safety.

Soil-screening results

The soil results did not show a systematic increase in the analysed metals with increasing wastewater exhaust-exposure time. Directly after application, Cd, Cu, Pb, Hg, Ni, Zn, and Cr were generally similar among variants or below the relevant quantification limits. Trace elements in soils can show high local variability because their concentrations depend on parent material, soil texture, organic matter, pH, redox conditions, and anthropogenic inputs (Kabata-Pendias, 2011). Therefore, small differences in single soil samples should be interpreted conservatively.

Pb values in wastewater-amended soil were slightly lower than in the untreated soil control. Cu remained within a narrow range, while Cd varied only modestly. These observations provide no indication of a strong immediate increase in the analysed metals following application of the tested wastewater. The six-day results were more variable. The comparatively high Zn value in the 30-min variant and the differences in Cr illustrate the limitations of single-sample soil analysis, because a single concentration value may depend strongly on sampling location, mixing, moisture, particle-size distribution, and the presence of local mineral or organic fractions.

The absence of *Salmonella* from the soil samples should also be interpreted cautiously. *Salmonella* was absent from the untreated soil control, and no soil variant receiving untreated *Salmonella*-positive wastewater was included. The soil results therefore confirm only that the organism was not detected in the analysed samples; they do not quantify persistence, transport, or inactivation in soil. This caution is consistent with risk-based wastewater guidance, which treats soil and crop exposure as part of a wider chain of health-risk management rather than as a single endpoint measurement (World Health Organization, 2006).

Environmental relevance of the mobile concept

The engineering value of the investigated system lies in combining an unavoidable transport operation with a gas-liquid process. This differs from most decentralized wastewater treatment approaches, which are usually designed as stationary on-site treatment solutions intended to reduce or eliminate transport needs (Massoud et al., 2009; Capodaglio, 2017). Recent studies on rural domestic wastewater treatment also emphasize decentralized process configurations adapted to local settlement patterns and infrastructure limitations (Li et al., 2024). The concept analysed here addresses a narrower situation in which wastewater is already collected and transported in a sanitation vehicle.

Using transport time as a process interval may reduce the need for a separate stationary contact tank. However, the apparent simplicity of the concept creates environmental and operational questions. The wastewater may receive both heat and combustion products. The exhaust line may experience additional backpressure. Tank materials and seals may be exposed to acidic condensates. Operators may be exposed during connection, sampling, and discharge. The chemical quality of the resulting wastewater may depend on engine operating conditions and vehicle maintenance.

Consequently, the microbial result cannot be considered independently of chemical transfer. An environmental benefit would require the reduction of microbiological hazard to outweigh any introduced chemical, occupational, or operational risk. For this reason, the present results should be regarded as screening data supporting further technical interpretation, not as certification of treatment effectiveness, regulatory compliance, or environmental safety.

CONCLUSIONS

Based on the results obtained in this work, the following conclusions were formulated:

- Two independent laboratory series showed a consistent qualitative change in Salmonella detectability during diesel-exhaust contact with domestic wastewater.
- Salmonella was detected or isolated in untreated and tank-contact control samples but was not detected after 30, 60, or 90 min of exhaust exposure.
- The first laboratory series indicated that the qualitative transition occurred between 15 and 30 min under the tested conditions.
- Intestinal parasite eggs were absent from both control and exposed wastewater samples, and the dataset therefore did not demonstrate an effect of the process on parasite eggs.
- Contact with the sanitation tank was associated with increases in several wastewater metals, particularly Cu and Zn, before the defined exhaust-exposure interval.
- Between 30 and 90 min, the analysed wastewater metals did not show a common monotonic increase with increasing exposure time.
- Soil screening did not reveal a systematic relationship between wastewater exhaust-exposure time and the concentrations of the analysed trace metals.
- The absence of quantitative microbiological data, experimental replication, exhaust characterization, and analysis of organic combustion-derived contaminants restricts the results to preliminary microbiological and trace-metal screening.

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REFERENCES

1. Agarwal, A., Ng, W.J., Liu, Y. (2011). Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere, 84*(9), 1175–1180. https://doi.org/10.1016/j.chemosphere.2011.05.054
2. Capodaglio, A.G. (2017). Integrated, decentralized wastewater management for resource recovery in rural and peri-urban areas. *Resources, 6*(2), 22. https://doi.org/10.3390/resources6020022
3. Durczak, K., Osuch, E., Podsiadlowski, S., Prawniczak, S., Przybył, J.J. (2020). System for biological pulverization inactivation of domestic wastewater in sanitation trailers. *Polish Patent PL* 235193 B1.
4. Kabata-Pendias, A. (2011). *Trace elements in soils and plants (4th ed.).* CRC Press.
5. Kostenidou, E., Karnezi, E., Hite, J.R., Kostenidis, S., Louvaris, E., Psichoudaki, M., ..., Pandis, S.N. (2021). Emission factors, chemical composition, and morphology of particles emitted from Euro 5 and Euro 6 gasoline and diesel vehicles. *Atmospheric Chemistry and Physics, 21*, 4779–4796. https://doi.org/10.5194/acp-21-4779-2021
6. Li, X., Zhang, J., Liu, J., Wang, S., Wang, Y. (2024). Application of decentralized wastewater treatment technology in rural domestic wastewater treatment. *Sustainability, 16*(19), 8635. https://doi.org/10.3390/su16198635
7. Liang, F., Lu, M., Keener, T.C., Liu, Z., Khang, S.J. (2005). The organic composition of diesel particulate matter, diesel fuel and engine oil of a non-road diesel generator. *Journal of Environmental Monitoring, 7*(10), 983–988. https://doi.org/10.1039/B504728E
8. Massoud, M.A., Tarhini, A., Nasr, J.A. (2009). Decentralized approaches to wastewater treatment and management: Applicability in developing countries. *Journal of Environmental Management, 90*(1), 652–659. https://doi.org/10.1016/j.jenvman.2008.07.001
9. Mohd Selihin, N., Tay, M.G. (2022). A review on future wastewater treatment technologies: Micro-nanobubbles, hybrid electro-Fenton processes, photocatalytic fuel cells, and microbial fuel cells. *Water Science and Technology, 85*(1), 319–336. https://doi.org/10.2166/wst.2021.618
10. Shen, W., Zhang, X., Huang, Y., Fu, J. (2022). Microbubble and nanobubble-based gas flotation for oily wastewater treatment: A review. *Environmental Reviews, 30*(3), 359–374. https://doi.org/10.1139/er-2021-0127
11. Temesgen, T., Bui, T.T., Han, M., Kim, T.I., Park, H. (2017). Micro and nanobubble technologies as a new horizon for water-treatment techniques: A review. *Advances in Colloid and Interface Science, 246*, 40–51. https://doi.org/10.1016/j.cis.2017.06.011
12. United States Environmental Protection Agency. (2002). Health assessment document for diesel engine exhaust. National Center for Environmental Assessment, Washington, DC.
13. World Health Organization. (2006). Guidelines for the safe use of wastewater, excreta and greywater. Volume 2: Wastewater use in agriculture. World Health Organization.