

Article

Characterization of Low-Volume Meat Processing Wastewater and Impact of Facility Factors

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Abstract: Low-volume meat processing facilities often rely on decentralized wastewater treatment due to cost constraints and the lack of access to centralized treatment. Improved characterization of these facilities' wastewater is crucial for meeting local groundwater discharge permits. This study also directly correlates treatment systems and facility characteristics to the results of the characterization. The total nitrogen (TN), biochemical oxygen demand (BOD), and phosphorus (P) reductions ranged from −15% to 83%, 43% to 95%, and −75% to 62%, respectively. Slaughtering and smoking were found to significantly increase nutrient concentrations. The average TN leaving the slaughterhouses and processing-only facilities was 519 mg/L-N and 154 mg/L-N, respectively. The average BOD produced by the slaughterhouses and processors was 3002 mg/L and 1660 mg/L, respectively. Filtration was found to reduce BOD, chemical oxygen demand (COD), and trace metals. Aeration in a treatment lagoon was found to significantly reduce BOD, COD, and N compounds. The results indicate that even simple decentralized wastewater treatment systems, combined with facility management practices, can substantially reduce permitted wastewater characteristics. The facility with the best BOD removal had an effluent value of 71.3 mg/L, representing a 96% reduction. The facility with the best TN removal had an effluent value of 20 mg/L, representing a 92% reduction prior to discharge.



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1. Introduction

Wastewater treatment is a significant challenge for meat processing facilities that use decentralized wastewater treatment, which are typically low-volume processors who may have low revenues and no access to a municipal centralized wastewater treatment plant. Generally, in the U.S., a groundwater discharge permit from their state or regional regulatory agency is required for these low-volume processors. An example of this is Groundwater Discharge General Permit GW1530000 from Michigan's Department of Environment, Great Lakes, and Energy (EGLE), which governs small-volume (<20,000 gallons of wastewater per day) meat processing facilities. These facilities typically dispose of the wastewater using land application; however, pretreatment is required because of the wastewater's high strength (Table 1), compared to domestic wastewater (Table 2).

The U.S. Environmental Protection Agency (EPA) is currently researching the impacts of wastewater from the meat slaughter and processing industry. The goal is to develop a better characterization of the wastewater and determine the effectiveness of management approaches to update policy [1].

Table 1. Characteristics of meat processing wastewater.

Constituent	Units	Min	Max	Data From
TN	mg/L	49	841	[2–4]
TKN	mg/L-N	67	1057	[2]
NH ₃	mg/L-N	36	75	[2]
NO ₃ and NO ₂	mg/L-N	0	3.3	[2,5]
P	mg/L-P	15	217	[4–7]
TSSs	mg/L	200	12,000	[4,7,8]
BOD	mg/L	200	4600	[4,7]
COD	mg/L	200	50,665	[2–4,7]
Alkalinity	mg/L as CaCO ₃	312	872	[2,5]

TKN—total Kjeldahl nitrogen; TSSs—total suspended solids; BOD—biological oxygen demand; COD—chemical oxygen demand.

Table 2. Characteristics of untreated domestic wastewater [9].

Constituent	Unit	Minimum	Maximum
TN	mg/L-N	26	75
P	mg/L-P	6	12
NH ₃	mg/L-N	4	13
TSS	mg/L	155	330
BOD	mg/L	155	286
COD	mg/L	500	660
FOG	Mg/L	70	105

TKN—total Kjeldahl nitrogen; TSSS—total suspended solids; BOD—biological oxygen demand; COD—chemical oxygen demand; FOG—fats; oil; and grease.

Pretreatment techniques, at a minimum, typically entail storage, settling, and fats, oil, and grease (FOG) flotation in a septic tank, followed by biological treatment in a lagoon prior to land application. Alternatively, a rapid infiltration basin is sometimes used to dispose of the wastewater.

Septic tanks lead to the separation of solids and FOG from wastewater. In domestic systems, this liquid is then discharged into a leach field, mound systems, or drip systems [10]. The materials remaining in the septic tank accumulate into sludge and scum layers that are pumped out as needed. For industrial and commercial systems, this water is often sent to other treatment units, such as a coagulation/flocculation tank or a membrane filter [6]. The addition of optional effluent filters in septic tanks improves the quality of the effluent water, resulting in upwards of 60% solids and 30% 5-day biological oxygen demand (BOD) removals [6,11]. Anaerobic conditions are present in these tanks; however, research is needed to determine if septic tanks also contribute to biological degradation [12]. Other systems are currently used to ensure this biological degradation occurs. The facilities observed in this study use treatment lagoons prior to land application or subsurface discharging.

Treatment lagoons exist in three main forms. Anaerobic lagoons, which are typically 3–6 m deep, rely primarily on anaerobic bacteria that are found in oxygen-deprived environments. Odor is a major concern with these lagoons, and they are typically not recommended if residences are nearby. Anaerobic lagoons also produce more methane, a major greenhouse gas, than the other lagoon types [13]. This methane, however, can be harvested as biogas and used as fuel, although this is likely not economical on a small scale. These lagoons typically have a 4–16-day retention time and can remove upwards of 60–80% of the BOD [7,14]. Aerobic lagoons are shallower, typically only 0.5–1.5 m deep. Algal growth and microorganisms treat the wastewater throughout the entire depth. Oxygen is maintained through a combination of photosynthesis, air diffusion, and mechanical aeration [7]. Facultative lagoons, which are utilized at all sites in this study, are typically up to 3 m deep and combine both aerobic and anaerobic environments. The upper layer of the lagoon is aerobic, while the deeper layer functions as an anaerobic system. BOD and chemical oxygen demand (COD) removal is in the range of 60–90%. These systems typically have

a retention time of 30–120 days [7]. In alkaline lagoons, precipitation reactions can occur, resulting in upwards of 50% P removal [15]. Depending on a variety of factors, especially detention time and pH, up to an 80% removal of ammonia (NH_3) was observed [15]. A case study focused on piggeries found similar efficacy, with 75% BOD removal and a heavily reduced odor, although this odor can become problematic in the fall and spring [15,16].

The final step for water leaving these facilities is land application. Soil uptake of wastewater pollutants is an important part of the decentralized wastewater treatment process. A substantial amount of BOD can be oxidized if the soil is not overloaded. Land application uses 50–70% less energy and reduces greenhouse gas emissions by an estimated 3000 metric tons per year when compared to activated sludge treatment [17]. Soil treatment is the primary reason that BOD is often regulated based on loading because the land application of high-strength wastewater can cause excessive biofilm growth, leading to high levels of moisture within the porosity of the soil. This can cause wastewater surfacing and anaerobic soil conditions, resulting in poor BOD removal and metal mobilization. Metal mobilization occurs when anaerobic metal-reducing microorganisms predominate and reduce natural soil metals, such as manganese, iron, and arsenic, enabling transport through the soil column [18]. Julien et al. found that soils have a maximum loading before BOD has a major impact on metal leaching [18], which is heavily dependent on soil type. The same study found that at least 12 h of rest between dosing events maximized soil aeration. Metal mobilization was found not to be significant if the volumetric soil moisture content remains below 25–30% [19,20]. This highlights why BOD treatment in lagoons is especially important when looking at these systems.

Nitrate (NO_3) is another important wastewater constituent, especially when entering groundwater. High NO_3 levels in groundwater can lead to methemoglobinemia, more commonly known as blue baby syndrome. Due to this risk, the U.S. EPA regulates at a 10 mg/L of N limit in groundwater [17]. Denitrification, the conversion of NO_3 to N gas, occurs under anaerobic conditions and requires carbon. Achieving denitrification while preventing metal leaching using soil treatment requires careful application [17]. Denitrification will occur in the anaerobic areas of a facultative lagoon, and proper treatment will minimize the risks of high levels of NO_3 in groundwater.

The complexity and lack of knowledge concerning the management of decentralized, high-strength wastewater, specifically that originating from meat processing, led to this research, which had the following project components.

1. Concentrations and variability in influent and lagoon wastewater constituents.
2. Facilities' characteristics' impacts on influent and lagoon wastewater constituents, such as facilities that slaughter and process and ones that only process.
3. Treatment effectiveness.
4. BOD loading compared to concentration for each facility.

2. Materials and Methods

The objective of this research was to characterize wastewater from six representative meat processors. Processors were selected assuming operations would result in typical low-volume meat slaughtering/processing wastewater, and the characterization of such wastewater would support policy development. The data were then analyzed to determine the performance of commonly used treatment units. This allows for the identification of technologies that are best suited for facility- and management-specific considerations. Included are choices between more extensive facility treatment vs. the implementation of enhanced management practices to separate the extreme wastewater components, such as blood and tissue, before land application.

The first stage of this process was to select processors in Michigan that are representative of the industry. This included key factors such as whether the facility slaughters, smokes meat, combines human wastewater, uses effluent filters, the detention time in septic tanks, and the lagoon operational strategy. Sample locations for the six selected

processors were determined. Thereafter, samples were collected, and data were analyzed. A description of each facility is shown in Table 3.

Table 3. Facility characteristics.

Facility	Aeration	Comingled Human Wastewater	Septic Tank Filter	Slaughter-House	Smokes Meat	Special Characteristics
A		✓	✓		✓	Two non-aerated lagoons in batch operation. One is actively filled, while the other provided detention time.
B	✓	✓	✓	✓		Lagoon aeration, 6–10 h/day, began partway through the sampling period. Commingling began partway through the sampling period.
C		✓	✓	✓	✓	Septic tank effluent filter but not accessible for sample collection.
D				✓	✓	Separate processing and slaughter wastewater samples were able to be collected. Two lagoons are used; only the first one is regularly used, as the second lagoon is a backup in case of overflow in the first.
E	✓			✓		Subsurface aeration occurs year-round, and surface aeration occurs during spring, summer, and fall.
F	✓	✓				Wash water from loading bay mixed in. Two infiltration lagoons in series; only second lagoon is aerated.

Generally, two locations were selected at each facility. Influent was collected near the process floor discharge, such as at the first septic tank, unless a high quantity of solids inhibited sampling. The second sample was from a lagoon, which may or may not represent that which was applied to the land, depending on the proximity to the time of lagoon discharge. Where applicable, samples were also collected after the septic tank effluent filter.

Six sampling events occurred: four in the summer, between the start of July and the end of August, and two in the fall, between October and November. All testing methods are listed in Table 4. Methods using HACH testing kits (Loveland, CO, USA) followed EPA methods whenever possible, as indicated in Table 4. The other parameters were measured by a state-certified commercial laboratory, Merit Laboratories (East Lansing, MI, USA). Organic nitrogen (organic N) was calculated by obtaining the difference between total Kjeldahl nitrogen (TKN) and NH_3 . Total inorganic nitrogen (TIN) was calculated by obtaining the difference between TN and organic N.

Table 4. Wastewater analytical methods.

Parameter	Method
TN (mg/L-N)	HACH 10208
Organic N (mg/L-N)	Calculated
NO_3 (mg/L-N)	40 CFR 141, HACH 10206
NH_3 (mg/L-N)	EPA 350.1, 351.1, 351.2, HACH 10205
TKN (mg/L-N)	4500-N(Org) C. Semi-Micro-Kjeldahl
TIN (mg/L-N)	Calculated
NO_2^- (mg/L-N)	HACH 10207
P (mg/L-P)	EPA365.1, 365.3, HACH 8190

Table 4. Cont.

Parameter	Method
BOD (mg/L)	SM 5210 B
COD (mg/L)	E410.4
TSSs (mg/L)	EPA 160.2
pH	HACH Lange 50 50 T Probe
Hardness (mg/L)	SM 2340 C
Alkalinity (mg/L-CaCO ₃)	SM 2320 B
FOG (mg/L)	E1664A
Ca (mg/L)	E200.8
Na (mg/L)	E200.8
Cu (mg/L)	E200.8
Mn (mg/L)	E200.8
Cl (mg/L)	E200.8
Zn (mg/L)	E200.8

Data were analyzed in SAS using PROC GLIMMIX (version 9.4, SAS Inst. Inc., Cary, NC, USA) as a completely randomized design. For all analyses, the processing facility was included as a fixed effect. Treatment least-squares means were separated with the PDIF option of SAS using a significance level of $p \leq 0.05$. The Kenward–Roger approximation was used for estimating denominator degrees of freedom for all analyses.

3. Results and Discussion

3.1. Variability and Concentrations of Influent

Tables 5–8 show the number of samples (n) and the average (Avg), minimum (Min), maximum (Max), and standard deviation (SD) for all the sampling events at all the facilities.

Table 5 shows the nutrient data. The TN content is the most variable, followed by the TKN content, which includes NH₃ and organic N levels. The organic N content also demonstrates a high degree of variability. NO₃ and nitrite (NO₂[−]) demonstrate the least variability and are important regarding public health. The Michigan groundwater discharge general permit GW1530000 established a limit of 1.0 mg/L of NO₂[−] for all types of lagoons and infiltration basins [21]. No facilities exceeded this limit, as the highest NO₂[−] lagoon wastewater value, which is ultimately land applied, was 0.21 mg/L. This is expected since NO₂[−] is inherently unstable and rapidly converts to NO₃ in most wastewater [22].

Table 5. Cumulative nutrient data.

Parameter	n	Avg	Min	Max	SD
TN Inf (mg/L-N)	38	354	51.4	1280	388
TN Lag (mg/L-N)	31	184	3.10	818	198
Organic N Inf (mg/L-N)	34	134	0.00	845	178
Organic N Lag (mg/L-N)	31	49.3	0.00	165	39.0
NO ₃ Inf (mg/L-N)	40	3.45	0.130	10.1	2.45
NO ₃ Lag (mg/L-N)	35	2.27	0.087	12.4	2.48
NH ₃ Inf (mg/L-N)	35	185	14.0	1024	285
NH ₃ Lag (mg/L-N)	31	137	0.014	715	186
TKN Inf (mg/L-N)	42	339	48.0	1260	366
TKN Lag (mg/L-N)	36	184	2.40	813	200
TIN Inf (mg/L-N)	34	225	17.2	1035	291
TIN Lag (mg/L-N)	29	134	1.80	720	182
NO ₂ [−] Inf (mg/L-N)	27	1.12	0.025	12.5	1.12
NO ₂ [−] Lag (mg/L-N)	22	0.062	0.03	0.21	0.04
P Inf (mg/L-P)	38	50.9	17.6	265	44
P Lag (mg/L-P)	33	41.9	3.78	264	47.5

Notes: Inf—influent; Lag—lagoon.

Table 6 contains data pertaining to wastewater carbon, both the BOD and COD. The BOD represents the oxygen consumed in the biological degradation of compounds in the wastewater. The COD utilizes a harsher oxidizer, allowing for the detection of more organic components than only those which are biologically degradable. The COD should always be higher than the BOD, provided that a nitrification inhibitor is used. The BOD-to-COD ratio helps determine how biodegradable the wastewater constituents are. A lower ratio indicates less rapidly biodegradable material is present in the wastewater. For domestic wastewater, the typical BOD/COD ratio is 40% [23]. In the current study, the ratio was higher than for domestic wastewater by the time the water reached the lagoon, which was unexpected. The reason for this difference is unclear but may be attributed to the high variability in the data, especially for the COD.

Table 6. Cumulative carbon data.

Parameter	<i>n</i>	Avg	Min	Max	SD
BOD Inf (mg/L)	39	2396	319	7900	2034
BOD Lag (mg/L)	36	635	24.0	4740	918
COD Inf (mg/L)	42	8880	692	76,800	13,300
COD Lag (mg/L)	36	1317	83.0	3880	1226
BOD/COD Ratio Inf		27%			
BOD/COD Ratio Lagoon		48.2%			

Notes: Inf—influent; Lag—lagoon.

Tables 7 and 8 contain total suspended solids (TSSs), pH, hardness, alkalinity, FOG, and several metals. The FOG content was greatly reduced at all facilities and did not appear to be an issue for land application or infiltration. One major source of pH variation was the use of caustic and acidic cleaning agents [7,24]. However, the inhibition of the biological process in the lagoon and the corrosion of the treatment infrastructure are unlikely to be a concern within this pH range, especially with the high alkalinity present in the water.

Table 7. Cumulative commonly measured parameter data.

Parameter	<i>n</i>	Avg	Min	Max	SD
TSSs Inf (mg/L)	29	1210	44.0	15,600	2850
TSSs Lag (mg/L)	25	787	20.0	7050	787
pH Inf	42	6.61	5.57	7.63	0.510
pH Lag	36	7.48	6.04	9.46	0.690
Hardness Inf (mg/L)	42	260	5.00	2440	375
Hardness Lag (mg/L)	36	246	100	384	94.7
Alkalinity Inf (mg/L-CaCO ₃)	42	746	170	2210	620
Alkalinity Lag (mg/L-CaCO ₃)	36	735	240	1700	458
FOG Inf (mg/L)	41	906	1.00	9470	1850
FOG Lag (mg/L)	36	12.5	1.00	101	21.3

Notes: Inf—influent; Lag—lagoon.

Table 8. Cumulative data on inorganics.

Parameter	<i>n</i>	Avg	Min	Max	SD
Calcium Inf (mg/L)	42	166	11.5	1540	253
Calcium Lag (mg/L)	36	62.9	21.6	131	29.7
Sodium Inf (mg/L)	42	299	36.0	637	189
Sodium Lag (mg/L)	36	266	66.9	731	179
Copper Inf (mg/L)	42	0.233	0.016	0.998	0.285
Copper lag (mg/L)	36	0.173	0.005	1.060	0.337
Manganese Inf (mg/L)	42	0.22	0.01	1.27	0.310

Table 8. Cont.

Parameter	<i>n</i>	Avg	Min	Max	SD
Manganese Lag (mg/L)	36	0.133	0.024	0.429	0.134
Chloride Inf (mg/L)	42	386	5.00	2700	474
Chloride Lag(mg/L)	36	332	49.0	993	280
Zinc Inf (mg/L)	42	1.047	0.07	5.73	1.40
Zinc Lag (mg/L)	36	0.268	0.005	1.67	0.478

Notes: Inf—influent; Lag—lagoon.

3.2. Impact of Facility Characteristics on Influent and Effluent Wastewater Characteristics

Tables 9–28 focus on the statistical analysis of wastewater for individual facility factors. The statistical analyses used the standard error of the mean (SEM). The factors included are slaughter (compared to processing only), meat smoking, human wastewater comingling, septic tank effluent filtration, and lagoon aeration.

Table 9 shows the impact of slaughtering on wastewater nutrients. Four of the facilities slaughter, while two process only. Slaughtering produced wastewater with greater ($p < 0.05$) concentrations of every nutrient except TN and influent NO_2^- . High variability may have contributed to the lack of significant differences, as the values for these characteristics when slaughtering were still higher compared to the values from the facilities that only process meat. NO_2^- is also typically not stable and is converted quickly to other forms of N.

Table 9. Slaughter–processing nutrient comparison.

Parameters (mg/L-Nor -P)	Slaughter	Processing	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TN Inf	519 ^a	154 ^b	87.4	37	0.003
TN Lag	215	89.3	69.5	24	0.132
TKN Inf	528 ^a	88.3 ^b	72.6	41	<0.001
TKN Lag	232 ^a	23.4 ^b	65.7	29	0.009
Organic N Inf	216 ^a	41.0 ^b	41.2	33	0.004
Organic N Lag	59.9 ^a	15.7 ^b	15.5	25	0.021
NH ₃ Inf	301 ^a	50.1 ^b	67.7	34	0.009
NH ₃ Lag	179 ^a	7.91 ^b	60.3	25	0.021
TIN Inf	360 ^a	53.1 ^b	68.1	33	0.002
TIN Lag	169 ^a	13.4 ^b	58.2	23	0.032
NO ₃ Inf	4.12 ^a	1.70 ^b	0.558	39	0.002
NO ₃ Lag	2.71	2.44	1.22	29	0.830
NO ₂ Inf	4.55	1.84	3.03	26	0.504
NO ₂ Lag	0.113 ^a	0.051 ^b	0.016	18	0.004
P Inf	64.1 ^a	34.5 ^b	10.9	37	0.003
P Lag	52.8	12.3	23.1	26	0.127

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ significantly ($p < 0.05$). Inf—influent; Lag—lagoon.

Table 10 shows the impact of slaughtering on the BOD and COD. The BOD ($p = 0.044$) and COD ($p < 0.001$) were both greater in the slaughterhouse wastewater influent compared to the wastewater influent from the facilities that only process. The primary source of this difference is blood, which has a COD of approximately 400,000 mg/L [7,24]. There was no difference ($p > 0.05$) for the BOD values in the lagoon, indicating that this type of treatment system effectively degrades the biological components in the wastewater, regardless of the differing influent characteristics. The lagoon COD was greater ($p = 0.012$) for the wastewater from the facilities that slaughtered compared to the only processing facilities. This indicates a greater presence of non-biodegradable compounds in slaughterhouse wastewater compared to wastewater from facilities that process only.

Table 10. Slaughter–processing carbon comparison.

Parameters (mg/L)	Slaughter	Processing	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
BOD Inf	3002 ^a	1660 ^b	490	38	0.044
BOD Lag	871	184	398	29	0.136
COD Inf	12,050 ^a	4870 ^b	2043	41	<0.001
COD Lag	1795 ^a	334 ^b	480	29	0.012

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Tables 11 and 12 show the impact of slaughtering on additional common wastewater characteristics and metals. Only pH and alkalinity differed, where both were greater ($p < 0.05$) in the influent and lagoon in the slaughter wastewater compared to the processing wastewater. No differences ($p > 0.05$) were observed in the influent or lagoon values for inorganic compounds when comparing the slaughter and processing wastewater.

Table 11. Slaughter–processing common measurements comparison.

Parameters (mg/L)	Slaughter	Processing	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TSSs Inf	1860	308	858	28	0.169
TSSs Lag	723	97.2	459	19	0.242
pH Inf	6.82 ^a	6.46 ^b	0.117	41	0.021
pH Lag	8.23 ^a	7.23 ^b	0.222	29	0.0004
Hardness Inf	334	147	90.8	41	0.123
Hardness Lag	249	249	43.6	29	0.996
Alkalinity Inf	966 ^a	455 ^b	141	41	0.0083
Alkalinity Lag	890 ^a	457 ^b	176	29	0.038
FOG Inf	645	1326	450	40	0.258
FOG Lag	67.3	2.17	58.2	29	0.544

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 12. Slaughter–processing inorganics comparison.

Parameters (mg/L)	Slaughter	Processing	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
Calcium Inf	211	108	61.6	41	0.209
Calcium Lag	70.1	65.9	12.9	29	0.767
Sodium Inf	328	288	45.7	41	0.508
Sodium Lag	266	387	72.1	29	0.148
Copper Inf	0.31	0.135	0.067	41	0.053
Copper Lag	0.252	0.014	0.148	29	0.162
Manganese Inf	4.09	0.336	2.57	41	0.271
Manganese Lag	0.160	0.139	0.058	29	0.752
Chloride Inf	419	349	117	41	0.647
Chloride Lag	328	477	117	29	0.267
Zinc Inf	1.12	24.2	14.8	41	0.241
Zinc Lag	0.387	0.034	0.210	29	0.142

Notes: Inf—influent; Lag—lagoon.

Table 13 shows the impact of smoking meat on wastewater nutrients. Four of the six facilities smoke meat regularly. The facilities with smoking have greater NO₃ and P levels in both the influent ($p = 0.023$ and $p = 0.007$) and lagoon ($p = 0.02$ and $p = 0.037$) samples than the facilities that do not smoke meat. The lagoon samples at these facilities

also showed greater TN ($p = 0.035$), TKN ($p = 0.009$), and NH₃ ($p = 0.036$) contents. This indicates that smoking meat interferes with the wastewater N treatment cycle.

Table 13. Smoking–no smoking nutrient comparison.

Parameters (mg/L-N or -P)	Smoking	No Smoking	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TN Inf	409	299	98.0	37	0.404
TN Lag	215 ^a	89.3 ^b	53.9	24	0.035
TKN Inf	399	270	89.0	41	0.274
TKN Lag	254 ^a	81.1 ^b	48.5	29	0.009
Organic N Inf	132	143	50.8	33	0.869
Organic N Lag	55.4	38.4	14.0	25	0.341
NH ₃ Inf	221	145	77.3	34	0.454
NH ₃ Lag	188 ^a	48.0 ^b	50.2	25	0.036
TIN Inf	273	170	78.7	33	0.331
TIN Lag	175	55.5	49.1	23	0.070
NO ₃ Inf	3.87 ^a	2.05 ^b	0.592	39	0.023
NO ₃ Lag	3.36 ^a	1.09 ^b	0.724	29	0.020
NO ₂ Inf	1.84	4.55	3.03	26	0.503
NO ₂ Lag	0.070	0.053	0.017	18	0.421
P Inf	69.5 ^a	31.7 ^b	9.77	37	0.007
P Lag	63.3 ^a	20.1 ^b	14.9	26	0.037

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 14 shows the impact of meat smoking on the BOD and COD. Both the BOD and COD in the influent ($p = 0.007$ and $p < 0.0001$) and lagoon ($p = 0.007$ and $p = 0.006$) samples are greater in the facilities that smoke than those that do not smoke meat. A high residual BOD (Table 14) prevents nitrification, which is one explanation for the higher TN and NH₃ (Table 13) contents in the lagoons of the smoking facilities [23].

Table 14. Smoking–no smoking carbon comparison.

Parameters (mg/L)	Smoking	No Smoking	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
BOD Inf	3230 ^a	1462 ^b	453	38	0.007
BOD Lag	1050 ^a	201 ^b	278	29	0.023
COD Inf	12,000 ^a	4950 ^b	2050	41	<0.0001
COD Lag	1990 ^a	681 ^b	347	29	0.006

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Tables 15 and 16 show the impact of meat smoking on additional common wastewater characteristics and metals. The facilities that smoke meat have samples with a greater influent pH ($p = 0.002$) and lagoon alkalinity ($p = 0.0155$) than those that do not smoke meat. The sodium content is the only inorganic parameter that was greater ($p = 0.015$) in the influent in the facilities that smoke meat compared to the facilities that do not smoke meat. The copper ($p = 0.036$), manganese ($p = 0.013$), and zinc ($p = 0.019$) concentrations were greater in the lagoon wastewater from the smoking facilities compared to the non-smoking facilities.

Table 17 shows the impact of comingling domestic wastewater on wastewater nutrients. Four of the six facilities comingled human wastewater, while two did not comeingle. Comingling demonstrated no impact ($p > 0.05$) on the influent water regarding nutrients. Likewise, the lagoon values were similar between the facilities that comeingle and do not comeingle human wastewater, with the exception of the TKN and NO₃ contents, which

were both greater ($p < 0.05$) at the facilities that comingle wastewater compared to those that do not.

Table 15. Smoking–no smoking common measurements comparison.

Parameters (mg/L)	Smoking	No Smoking	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TSSs Inf	762	1910	835	28	0.310
TSSs Lag	638	490	390	19	0.757
pH Inf	6.81 ^a	6.32 ^b	0.1103	41	0.002
pH Lag	7.51	7.32	0.205	29	0.465
Hardness Inf	258	254	93.6	41	0.974
Hardness Lag	219	297	30	29	0.050
Alkalinity Inf	853	615	151	41	0.235
Alkalinity Lag	958 ^a	543 ^b	127	29	0.0155
FOG Inf	1377	335	439	40	0.079
FOG Lag	84.6	3.64	69.3	29	0.365

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 16. Smoking–no smoking inorganics comparison.

Parameters (mg/L)	Smoking	No Smoking	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
Calcium Inf	186	143	62.7	41	0.61
Calcium Lag	66.8	66.7	66.8	29	0.991
Sodium Inf	364 ^a	222 ^b	42.5	41	0.015
Sodium Lag	319	246	54.2	29	0.293
Copper Inf	0.264	0.200	0.070	41	0.487
Copper Lag	0.314 ^a	0.022 ^b	0.104	29	0.036
Manganese Inf	4.27	0.202	2.57	41	0.232
Manganese Lag	0.204 ^a	0.076 ^b	0.038	29	0.013
Chloride Inf	440	320	116.73	41	0.435
Chloride Lag	353	367	88.6	29	0.903
Zinc Inf	1.29	23.9	14.8	41	0.250
Zinc Lag	0.487 ^a	0.031 ^b	0.144	29	0.019

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 17. Comingling–no comingling nutrient comparison.

Parameters (mg/L-N or -P)	Comingling	No Comingling	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TN Inf	344	133	163	31	0.246
TN Lag	223	81.1	67.1	24	0.081
TKN Inf	341	142	145	35	0.220
TKN Lag	235 ^a	81.1 ^b	58.6	29	0.034
Organic N Inf	116	65.5	64.4	28	0.473
Organic N Lag	54.6	42.8	16.9	25	0.549
NH ₃ Inf	190	95.5	151	28	0.570
NH ₃ Lag	169	46.2	63.5	25	0.106
TIN Inf	232	108	155	27	0.468
TIN Lag	157	52.3	61.6	23	0.158
NO ₃ Inf	3.35	1.81	1.04	33	0.188
NO ₃ Lag	2.67 ^a	1.01 ^b	0.595	29	0.025
NO ₂ Inf	4.06	0.045	5.33	23	0.501
NO ₂ Lag	0.060	0.045	0.060	17	0.203

Table 17. Cont.

Parameters (mg/L-N or -P)	Comingling	No Comingling	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
P Inf	60.1	38.8	19.2	31	0.329
P Lag	55.5	22.4	18.2	26	0.144

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 18 shows the impact of comingling on the BOD and COD. The COD was greater in both the influent ($p < 0.0001$) and the lagoon ($p < 0.034$). The greater organic content puts an extra burden on land application treatment.

Table 18. Comingling–no comingling carbon comparison.

Parameters (mg/L)	Comingling	No Comingling	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
BOD Inf	2700	1770	900	32	0.361
BOD Lag	942	192	336	29	0.069
COD Inf	10,100 ^a	6200 ^b	2430	35	<0.0001
COD Lag	1820 ^a	711 ^b	424	29	0.034

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Tables 19 and 20 show the impact of comingling on common wastewater characteristics and metals. The influent TSSs content for the comingled facilities was unexpectedly much lower ($p = 0.0098$) when compared to the facilities that did not comeingle; however, the TSSs content was similar ($p > 0.05$) in the lagoon samples regardless of comingling practices. The influent pH was greater ($p = 0.010$) at the facilities that comeingle human wastewater compared to those that do not. However, the lagoon pH values were comparable ($p > 0.05$).

Table 19. Comingling–no comingling common measurements comparison.

Parameters (mg/L)	Comingling	No Comingling	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TSSs Inf	640 ^a	4880 ^b	1360	24	0.0098
TSSs Lag	664	185	527	20	0.413
pH Inf	6.75 ^a	6.15 ^b	0.198	35	0.010
pH Lag	7.50	7.15	0.227	29	0.203
Hardness Inf	232	170	166	35	0.735
Hardness Lag	236	298	36.5	29	0.162
Alkalinity Inf	738	284	240	35	0.095
Alkalinity Lag	915 ^a	532 ^b	150	29	0.039
FOG Inf	1150	812	819	34	0.709
FOG Lag	73.2	3.88	81.7	29	0.476

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Three of the six facilities have filters installed. Table 21 shows the impact of an effluent septic tank filter within a system on nutrients. The filter lowered all values, but not significantly ($p > 0.05$).

Table 22 shows the impact of an effluent septic tank filter within a system on the BOD and COD. Both parameters demonstrate a significant decrease ($p < 0.0001$) of 59% and 69%, respectively, between the influent and the post-filter samples. These decreases indicate that filters are an effective pre-treatment for both parameters, which is consistent with findings from others [11].

Table 20. Comingling–no comingling inorganics comparison.

Parameters (mg/L)	Comingling	No Comingling	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
Calcium Inf	160	144	111	35	0.897
Calcium Lag	67.9	67.9	11.2	29	0.999
Sodium Inf	312 ^a	51.3 ^b	58.5	35	0.0003
Sodium Lag	339	199	61.8	29	0.064
Copper Inf	0.233	0.262	0.114	35	0.816
Copper Lag	0.271	0.028	0.127	29	0.114
Manganese Inf	2.53	0.324	4.77	35	0.676
Manganese Lag	0.185	0.077	0.047	29	0.060
Chloride Inf	375	27.2	189	35	0.104
Chloride Lag	424	246	102	29	0.149
Zinc Inf	14.7	0.715	27.4	35	0.646
Zinc Lag	0.423	0.035	0.176	29	0.072

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 21. In-facility filter nutrient comparison.

Parameters (mg/L-Nor -P)	Influent	Post-Filter	Lagoon	Statistics		
				SEM	<i>n</i>	<i>p</i> -Value
TN	440 ^a	273 ^{ab}	99.5 ^b	84.9	36	0.027
TKN	332 ^a	222 ^{ab}	60.8 ^b	67.7	36	0.027
Organic N	164 ^a	108 ^{ab}	30.3 ^b	47.4	34	0.869
NH ₃	144 ^a	90.2 ^{ab}	30.6 ^b	37.7	36	0.120
TIN	171 ^a	108 ^{ab}	36.9 ^b	39.6	36	0.071
NO ₃	3.23	2.78	2.33	0.666	36	0.643
NO ₂	0.098	0.083	0.081	3.03	19	0.721
P	32.5 ^a	31.3 ^a	14.3 ^b	3.48	31	0.001

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly.

Table 22. In-facility filter carbon comparison.

Parameters (mg/L)	Influent	Post-Filter	Lagoon	Statistics		
				SEM	<i>n</i>	<i>p</i> -Value
BOD	2730 ^a	1320 ^b	225 ^c	266	36	<0.0001
COD	9275 ^a	2846 ^b	640 ^c	1203	36	<0.0001

Notes: ^{a–c} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly.

Tables 23 and 24 show the impact of an effluent septic tank filter within a system on other common wastewater characteristics and metals. The lagoon FOG ($p = 0.021$), calcium ($p = 0.0006$), copper ($p = 0.001$), zinc ($p < 0.0001$), and sodium ($p = 0.005$) concentrations were lower than in the influent. The pH of the system showed progressive increases ($p = 0.0003$) at each sampling facility from the influent to the lagoon. This increase is observed in all the facilities and is likely not due to a filter. Surprisingly, the TSSs content decreased numerically but not significantly ($p > 0.05$) throughout the system. This is contradictory to the review paper by Mittal, which demonstrated a 50–70% reduction [11]. Data variability may be a factor. A finer filter is one option to increase TSSs removal to prevent finer suspended particles from escaping the filter.

Table 23. In-facility filter common measurements comparison.

Parameters (mg/L)	Influent	Post-Filter	Lagoon	Statistics		
				SEM	<i>n</i>	<i>p</i> -Value
TSSs	1160	664	260	582	24	0.432
pH	6.81 ^a	7.31 ^b	7.91 ^c	0.198	36	0.0003
Hardness	284	396	281	51.3	36	0.210
Alkalinity	927 ^a	867 ^a	521 ^b	112	36	0.032
FOG	1800 ^a	34.4 ^b	2.92 ^b	494	36	0.021

Notes: ^{a-c} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 24. In-facility filter inorganics comparison.

Parameters (mg/L)	Influent	Post-Filter	Lagoon	Statistics		
				SEM	<i>n</i>	<i>p</i> -Value
Calcium	224 ^a	117 ^b	69.0 ^b	26.0	36	0.0006
Sodium	644 ^a	489 ^b	419 ^b	46.4	36	0.005
Copper	0.256 ^a	0.056 ^b	0.012 ^b	0.044	36	0.001
Manganese	0.251	0.118	0.110	0.060	36	0.191
Chloride	871	635	604	84.0	36	0.061
Zinc	1.97 ^a	0.198 ^b	0.031 ^b	0.30	36	<0.0001

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 25 shows the impact of lagoon aeration on nutrients. Three of the six facilities utilize lagoon aeration. Aeration has a significant effect on TN, with a 67% reduction. The TKN was greater ($p = 0.012$) in the non-aerated lagoon samples compared to the aerated samples. This was expected since the conversion of TKN to NO_3 is an aerobic process. Aerobic denitrification has been demonstrated in mixed microbial communities, like the lagoons observed in this study [25]. Lower amounts of aeration were found to be more efficient than conventional denitrification [25]. This explains the NO_3 reductions observed in the aerated lagoons. In addition, the lagoons studied would also have anaerobic pockets where anaerobic denitrification or an alternative pathway such as anammox could occur. Strategic aeration proves to be an effective aid in reducing N levels.

Table 25. Aeration–no aeration nutrient comparison.

Parameters (mg/L-N or -P)	Aeration	No Aeration	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TN Lag	77.4 ^a	233 ^b	59.3	24	0.042
TKN Lag	72.4 ^a	246 ^b	53.3	29	0.012
Organic N Lag	32.7	59.1	15.07	25	0.150
NH_3 Lag	44.1	176	57.7	25	0.064
TIN Lag	52.8	164	56.4	23	0.116
NO_3 Lag	0.091 ^a	2.79 ^b	0.537	29	0.007
NO_2 Lag	0.053	0.057	0.008	17	0.674
P Lag	20.3	58.6	16.8	26	0.078

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 26 shows the impact of lagoon aeration on the BOD and COD. Aeration also had an impact on the BOD ($p = 0.036$) and COD ($p = 0.002$), with an 83% and 75% reduction, respectively, compared to the non-aerated lagoon samples. A greater reduction in the BOD also has a major and positive impact on N removal, as nitrification does not proceed until most of the BOD is oxidized.

Table 26. Aeration–no aeration carbon comparison.

Parameters (mg/L)	Aeration	No Aeration	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
BOD Lag	167 ^a	991 ^b	311	29	0.036
COD Lag	490 ^a	1979 ^b	364	29	0.002

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Tables 27 and 28 show the impact of lagoon aeration on common other wastewater characteristics and metals. The alkalinity was lower ($p = 0.02$) in the aerated lagoons, which was expected with improved N removal. The sodium ($p = 0.011$), manganese ($p = 0.032$), and zinc ($p = 0.047$) levels were also lower in the aerated samples compared to the non-aerated samples; however, the cause of this is unknown.

Table 27. Aeration–no aeration common measurements comparison.

Parameters (mg/L)	Aeration	No Aeration	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
TSSs Lag	490	636	378	20	0.752
pH Lag	7.29	7.45	0.220	29	0.547
Hardness Lag	289	237	34.7	29	0.228
Alkalinity Lag	525 ^a	937 ^b	139	29	0.020
FOG Lag	3.78	76.7	76.9	29	0.438

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

Table 28. Aeration–no aeration inorganics comparison.

Parameters (mg/L)	Aeration	No Aeration	Statistics		
			SEM	<i>n</i>	<i>p</i> -Value
Calcium Lag	67.1	68.2	10.5	29	0.930
Sodium Lag	176 ^a	356 ^b	55.0	29	0.011
Copper Lag	0.025	0.284	0.118	29	0.080
Manganese Lag	0.074 ^a	0.192 ^b	0.043	29	0.032
Chloride Lag	272	421	97.4	29	0.214
Zinc Lag	0.033 ^a	0.444 ^b	0.164	29	0.047

Notes: ^{a,b} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Inf—influent; Lag—lagoon.

3.3. Treatment Effectiveness

Tables 29–32 show the wastewater treatment effectiveness at each facility. The “Decrease” heading is the percent reduction for the parameters based on the influent and effluent values. A weighted average is used for the Facility D influent, as the slaughter and process streams were collected and analyzed individually. The “Discharge” heading is calculated from the lagoon measurements closest to when the contents within the lagoon were applied to land, as described below.

Facility A: Lagoon drainage occurred soon after the last summer collection. Consequently, the final summer value is assumed to be closest to discharge.

Facility B: Lagoon drainage occurred in the fall after fall collections. Consequently, the average of the fall values was used.

Facility C: The lagoon was pumped over a 5-day period in November. Consequently, the sample collected during this time was assumed to be the discharge value.

Facility D: Lagoon drainage occurred throughout October and November. Consequently, the first fall collection occurred during this period, and that value was used.

Facility E: The lagoon is drained monthly during the summer. Consequently, the average of the summer values was used.

Facility F: The lagoon utilizes an infiltration basin instead of land application. Consequently, the average of all the lagoon samples was used.

Table 29 compares the concentrations of nutrients between the facilities. The NO_2^- values were similar ($p > 0.05$) in the lagoon. These values are also well below the 1.0 mg/L limit, as specified in the GW1530000 permit for Michigan. Facility C had the highest value for NO_2^- leaving the facility, and that still demonstrated a 99% reduction. Consequently, NO_2^- is not of concern in these meat processing facilities. Most facilities experienced a decrease in TN, ranging from 65 to 26%, most likely indicating that an effective nitrification/denitrification process is occurring in the lagoons. However, microbial processes can also produce nitrous oxide (N_2O), a gas that has a major impact on global warming. This is likely not a concern in these systems, as Harper et al. found that on a swine production farm, 43% of the N entering the wastewater treatment system was lost through lagoons as N_2 . Only 0.1% was emitted as N_2O , and 8% of losses occurred due to NH_3 volatilization [26].

Table 30 compares the BOD and COD between each location. The BOD varied ($p < 0.05$) in both the influent and lagoon samples. Facility C had greater ($p < 0.05$) BOD values than all the other facilities, which were similar ($p > 0.05$). Facilities C and D showed an increase in the discharge value when compared to the average lagoon values. This likely resulted from the variability in the values and the continuous addition of wastewater to the lagoon. Facility A demonstrated the greatest removal for both BOD and COD, likely due to the long treatment time in the second holding lagoon where, wastewater is not continually added.

Table 29. Nutrients by location.

Parameter (mg/L-N or -P)	Facility							Statistics		
	A Co, F, Sm	B Ae *, Co *, F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	n	p-Value
TN Inf	254 ^c	626 ^b	1064 ^a	116 ^c	370 ^{bc}	133 ^c	71.7 ^c	128	38	<0.0001
TN Lag	89.3 ^c	110 ^c	484 ^a		229 ^b	59.8 ^c	80.2 ^c	44.5	31	<0.0001
TN Decrease	65%	83%	54%		26%	55%	−15%			
TN Discharge	20.0	101	489		264	57.9				
TN Discharge Decrease	92%	84%	54%		15%	56%				
TKN Inf	91.7 ^c	572 ^b	1021 ^a	107 ^c	377 ^b	142 ^c	61.8 ^c	68.5	42	<0.0001
TKN Lag	23.4 ^d	97.0 ^c	482 ^a		258 ^b	67.9 ^{cd}	56.8 ^{cd}	18.9	36	<0.0001
TKN Decrease	74%	62%	53%		2%	52%	−1%			
TKN Discharge	3.9	85.5	484		302	57.1				
TKN Discharge Decrease	96%	85%	53%		−15%	60%				
Organic N Inf	59.0 ^b	292 ^a	167 ^{ab}	23.8 ^b	301 ^a	65.5 ^b	35.4 ^b	77.3	34	0.0189
Organic N Lag	15.7 ^c	41.9 ^{abc}	80.4 ^a		78.2 ^{ab}	34.8 ^{bc}	28.9 ^c	16.2	31	0.0144
Organic N Decrease	73%	79%	58%		68%	47%	6%			
Organic N Discharge	3.76	33.2	29.8		83.6	28.5				
Organic N Discharge Decrease	94%	89%	82%		66%	56%				
NH ₃ Inf	32.6 ^c	255 ^b	877 ^a	87.4 ^c	57.8 ^c	95.5 ^c	29 ^c	58.7	35	<0.0001
NH ₃ Lag	7.91 ^c	53.3 ^c	419 ^a		173 ^b	38.4 ^c	26 ^c	24.4	31	<0.0001
NH ₃ Decrease	76%	79%	51%		−151%	60%	−4%			
NH ₃ Discharge	0.14	52.3	479		218	28.6				
NH ₃ Discharge Decrease	99%	80%	45%		−216%	70%				

Table 29. Cont.

Parameter (mg/L-N or -P)	Facility							Statistics		
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	n	p-Value
TIN Inf	38.4 ^c	302 ^b	905 ^a	92.1 ^{cd}	194 ^{bc}	108 ^{cd}	44.2 ^{cd}	61.1	34	<0.0001
TIN Lag	13.4 ^c	60.3 ^c	417 ^a		176 ^b	46 ^c	49 ^c	26.7	29	<0.0001
TIN Decrease	67%	80%	54%		−58%	57%	−5%			
TIN Discharge	12.6	53.8	484		266	29.5				
TIN Discharge Decrease	37%	82%	47%		−139%	73%				
NO ₃ Inf	2.99 ^{bcd}	3.46 ^{bc}	6.92 ^a	1.34 ^{de}	4.76 ^b	1.81 ^{cde}	0.340 ^e	0.73	40	<0.0001
NO ₃ Lag	2.71 ^{ab}	1.95 ^b	4.94 ^a		2.43 ^{ab}	0.698 ^b	0.600 ^b	0.969	35	0.0222
NO ₃ Decrease	10%	43%	35%		40%	61%	−130%			
NO ₃ Discharge	0.455	1.37	3.61		0.985	0.677				
NO ₃ Discharge Decrease	85%	60%	48%		76%	63%				
NO ₂ Inf	0.113 ^b	0.091 ^b	6.71 ^a	0.052 ^b	0.061 ^b	0.045 ^b	0.047 ^b	1.17	26	0.0011
NO ₂ Lag	0.07	0.07	0.046		0.052	0.046	0.045	0.022	22	0.0642
NO ₂ Decrease	38%	23%	99%		2%	0%	20%			
NO ₂ Discharge	0.07	0.07	0.05		0.07	0.035				
NO ₂ Discharge Decrease	38%	23%	99%		−32%	24%				
P Inf	32.8 ^c	32.3 ^c	82.9 ^{ab}	45.5 ^{bc}	108 ^a	38.8 ^{bc}	20.0 ^c	17.3	38	0.0014
P Lag	12.3 ^c	15.9 ^c	72.75 ^{ab}		99.6 ^a	23.4 ^{bc}	33.3 ^{bc}	18.6	27	0.0022
P Decrease	62%	51%	12%		9%	40%	−75%			
P Discharge	3.78	17.2	82.5		84.8	21.5				
P Discharge Decrease	88%	47%	0%		23%	45%				

Notes: ^{a–e} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Ae = aerated lagoon; Co = comingled; F = filter; S = slaughterhouse; Sm = smoking. * Facility B added aeration and comingling during the sample collection period. Inf—influent; Lag—lagoon.

The COD varied ($p < 0.05$) by facility, and the two influent wastewater flows at facility D - one was from the slaughter operation and the other was from processing. The discharge value of facility A is abnormal, as the COD is expected to be higher than the BOD.

Tables 31 and 32 compare other commonly measured wastewater characteristics and metals. The TSSs content was similar ($p > 0.05$) between the facilities in the lagoon treatment. Facilities B and C demonstrated an interesting increase in TSSs, attributed to the high quantity of algae when compared to the other facilities. The pH values varied ($p < 0.05$) between the facilities in both the influent and lagoon samples but had a consistent, slight increase at all the facilities. This increase is assumed to be caused by microbial denitrification, as evident by the reduction in TN. The alkalinity levels increased at some facilities, likely because of the varying levels of denitrification and nitrification between the facilities. The cleaning products used at each facility also contribute to the overall alkalinity of the system, as many cleaners and sanitizers contain sodium hydroxide. The influent FOG content was highly variable but different ($p < 0.05$), but it was consistently low in the lagoon samples.

Tables 29–32 demonstrate noticeable differences between the discharge values and the average lagoon values collected over the entire sampling period. Facility A demonstrated the ideal situation, as the treatment progresses throughout the entire summer in the second lagoon that does not receive wastewater. The lagoon is land-applied in the early fall after the maximum amount of treatment is achieved. The average TN removal at this facility for all sampling events was 65%, but the value closest to when it was land applied was 92%. This was also true for the TKN, NO₃, and P concentrations, which were 96%, 84%, and 88%, respectively, prior to land application compared to 74%, 10%, and 62%, respectively, over the entire sampling period. In contrast, Facility D demonstrated the opposite trend for TIN and NH₃ concentrations, most likely due to the sample location and the continuous influent into the lagoons even immediately before discharging. The only notable difference

in BOD and COD was in Facility C, which went from 57% to a 25% BOD removal. These examples highlight the necessity of basing regulations on the sampling closest to discharge.

Table 30. Carbon by location.

Parameter (mg/L)	Facility and Characteristics							Statistics		
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	<i>n</i>	<i>p</i> -Value
BOD Inf	3509 ^{ab}	1955 ^{bc}	4928 ^a	602 ^c	3803 ^a	1774 ^c	556 ^c	651	39	<0.0001
BOD Lag	184 ^b	275 ^b	2113 ^a		856 ^b	139 ^b	243 ^b	255	36	<0.0001
BOD Decrease	95%	86%	57%		72%	92%	42%			
BOD Discharge	119	273	3720		1060	71.3				
BOD Discharge Decrease	97%	86%	25%		65%	96%				
COD Inf	11,723 ^b	6828 ^d	9010 ^c	1090 ^g	26,156 ^a	6206 ^e	1117 ^f	1770	42	<0.0001
COD Lag	334 ^c	945 ^c	3188 ^a		2443 ^b	435 ^c	553 ^c	225	36	<0.0001
COD Decrease	97%	86%	65%		88%	93%	63%			
COD Discharge	83	640	2950		3200	364				
COD Discharge Decrease	99%	91%	67%		84%	94%				

Notes: ^{a–g} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Ae = aerated lagoon; Co = comingled; F= filter; S = slaughterhouse; Sm = smoking. * Facility C added aeration and comingling during the sample collection period. Inf—influent; Lag—lagoon.

Table 31. Commonly measured characteristics by location.

Parameter (mg/L)	Facility and Characteristics							Statistics		
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	<i>n</i>	<i>p</i> -Value
TSSs Inf	600	695	333	318	1614	4875	140	1900	29	0.1954
TSSs Lag	97.2	746	482		1196	185	193	475	24	0.36
TSSs Decrease	84%	−189%	−45%		7%	97%	−8%			
TSSs Discharge	64	293	298		1070	53.3				
TSSs Discharge Decrease	89%	58%	11%		17%	99%				
pH inf	6.80 ^{ab}	6.42 ^{bc}	6.80 ^{ab}	7.19 ^a	6.47 ^{bc}	6.14 ^c	6.42 ^{bc}	0.172	42	0.0037
pH Lag	8.23 ^a	7.58 ^{abc}	6.97 ^c		7.33 ^{bc}	7.05 ^c	7.73 ^{ab}	0.24	36	0.0068
pH Decrease	−21%	−18%	−12%		−10%	−15%	−17%			
pH Discharge	9.46	7.8	7.4		7.59	6.91				

Table 31. Cont.

Parameter (mg/L)	Facility and Characteristics							Statistics		
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	<i>n</i>	<i>p</i> -Value
pH Discharge Decrease	−40%	−22%	−9%		−14%	−13%				
Hardness Inf	105	463	83.3	223	621	170	151	143	42	0.087
Hardness Lag	249 ^a	311 ^a	117 ^c		345 ^a	286 ^{ab}	166 ^c	21.2	36	<0.0001
Hardness Decrease	−7%	32%	−66%		33%	−68%	−4%			
Hardness Discharge	164	296	124		368	304				
Hardness Discharge Decrease	−56%	36%	−49%		29%	−79%				
Alkalinity Inf	429 ^d	1305 ^b	1880 ^a	708 ^c	396 ^d	284 ^d	220 ^d	95.2	42	<0.0001
Alkalinity Eff	458 ^{cd}	583 ^c	1468 ^a		1101 ^b	501 ^{cd}	299 ^d	83.0	36	<0.0001
Alkalinity Decrease	−6.8%	55%	22%		−126%	−76%	−55%			
Alkalinity Discharge	268	600	1550		1086	516				
Alkalinity Discharge Decrease	38%	54%	−5%		−122%	81%				
FOG-Inf	3556 ^a	44 ^c	42.5 ^c	107 ^{bc}	1890 ^{ab}	811 ^{bc}	53.6 ^c	651	41	0.0009
FOG-Lag	2.16 ^b	3.67 ^b	14.0 ^{ab}		37 ^a	4.16 ^b	18.2 ^{ab}	8.56	35	0.0476
FOG decrease	100%	92%	67%		98%	99%	83%			
FOG Discharge	1	2	12		101	3.5				
FOG Discharge Decrease	100%	92%	72%		95%	100%				

Notes: ^{a-d} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Ae = aerated lagoon; Co = comingled; F= filter; S = slaughterhouse; Sm = smoking. * Facility C added aeration and comingling during the sample collection period. Inf—influent; Lag—lagoon.

Table 32. Inorganic Compounds by location.

Parameters (mg/L)	Facility							Statistics		
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	<i>n</i>	<i>p</i> -Value
Calcium Inf	215 ^{ab}	233 ^{ab}	20.3 ^b	61.1 ^b	447 ^a	144 ^b	42.4 ^b	93.3	42	0.0364
Calcium Lag	70.1 ^b	67.7 ^b	25.0 ^c		105 ^a	68.6 ^b	40.9 ^c	6.66	36	<0.0001
Calcium Decrease	67%	71%	−23%		70%	52%	23%			
Calcium Discharge	44.8	67	24.1		32.8	73.8				
Calcium Discharge Decrease	79%	71%	−19%		91%	49%				

Table 32. Cont.

Parameters (mg/L)	Facility						Statistics			
	A Co, F, Sm	B Ae *, Co , F, S	C Co, F, S, Sm	D-Proc Sm	D-Slau S, Sm	E Ae, S	F Ae, Co	SEM	n	p-Value
Sodium Inf	456 ^{ab}	522 ^a	257 ^c	418 ^b	323 ^c	51.3 ^d	63.9 ^d	32.0	42	<0.0001
Sodium Lag	387 ^a	450 ^a	214 ^b		357 ^a	78.7 ^b	109 ^b	47.4	36	<0.0001
Sodium Decrease	15%	14%	17%		−3%	−53%	−80%			
Sodium Discharge	234	357	226		353	84.4				
Sodium Discharge Decrease	49%	32%	12%		−2%	−65%				
Copper Inf	0.273 ^b	0.238 ^{bc}	0.032 ^c	0.04 ^c	0.01 ^a	0.262 ^{bc}	0.08 ^{bc}	0.08	42	<0.0001
Copper Lag	0.014 ^b	0.011 ^b	0.022 ^b		0.904 ^a	0.035 ^b	0.053 ^b	0.026	36	<0.0001
Copper Decrease	95%	95%	30%		−72%	87%	−55%			
Copper Discharge	0.005	0.006	0.015		0.017	0.05				
Copper Discharge Decrease	98%	97%	53%		97%	81%				
Manganese Inf	0.115 ^{bc}	0.386 ^{ab}	0.103 ^{bc}	0.061 ^c	0.530 ^a	0.32 ^{abc}	0.02 ^c	0.109	42	0.0140
Manganese Lag	0.139 ^b	0.081 ^{bc}	0.087 ^{bc}		0.385 ^a	0.074 ^{bc}	0.028 ^c	0.027	36	<0.0001
Manganese Decrease	−21%	79%	15%		7%	77%	−24%			
Manganese Discharge	0.036	0.07	0.081		0.969	0.070				
Manganese Discharge Decrease	69%	82%	21%		−134%	78%				
Chloride Inf	442 ^{ab}	828 ^a	150 ^b	495 ^{ab}	673 ^a	27.1 ^b	83.7 ^b	166	42	0.0089
Chloride Lag	477 ^b	730 ^a	138 ^c		445 ^b	62.0 ^c	136 ^c	61.8	36	<0.0001
Chloride Decrease	−8%	12%	8%		30%	−128%	36%			
Chloride Discharge	303	768	146		2700	68.3				
Chloride Discharge Decrease	31%	7%	3%		−324%	−152%				
Zinc Inf	2.61 ^a	1.34 ^{ab}	0.187 ^b	0.119 ^b	2.25 ^a	0.713 ^b	0.112 ^b	0.440	42	0.0004
Zinc Lag	0.034 ^b	0.028 ^b	0.133 ^b		1.29 ^a	0.039 ^b	0.079 ^b	0.046	36	<0.0001
Zinc Decrease	99%	98%	29%		23%	94%	−15%			
Zinc Discharge	0.005	0.024	0.082		3.64	0.045				
Zinc Discharge Decrease	100%	98%	56%		−117%	94%				

Notes: ^{a–d} Within a row, least-squares means without a common superscript differ ($p < 0.05$) significantly. Ae = aerated lagoon; Co = comingled; F= filter; S = slaughterhouse; Sm = smoking. * Facility B added aeration and comingling during the sample collection period. Inf—influent; Lag—lagoon.

3.4. BOD Concentration and Loading

In addition to concentrations, limits for loadings are also specified in permits. GW1530000 specifies a limit of 50 lb of BOD/acre-day (56 kg/ha-day) for land application to prevent metal mobilization [21]. This is calculated by multiplying the concentration and flow and dividing by the amount of land the wastewater is applied to. Table 33 lists the kg of BOD produced at each facility per day, but data on the area of the land it was applied to were not available. The importance of considering loadings is observed by comparing Facilities A and D. Both have similar average BOD concentrations, but the differences in flow rates result in a loading of 13.3 kg of BOD/day being produced by Facility A and 135.2 kg of BOD/day for the slaughter side of Facility D.

Table 33. Influent BOD concentration and loading.

Facility	Concentration (mg/L)			Loading (kg/Day)		
	Avg	Min	Max	Avg	Min	Max
A	3510	1206	4920	13.3	4.58	18.6
B	1960	660	3000	14.8	4.98	22.7
C	4930	1740	7900	41.4	14.6	66.2
D-Proc	602	460	966	7.12	5.44	11.4
D-Slau	3803	651	7470	135	23.1	265
E	1770	1020	3300	1.67	2.11	6.80
F	319	1050	556	12.1	39.7	21.0

4. Conclusions

Facility A, which carries out meat processing only, had superior wastewater nutrient constituent removals, with a TN reduction of 92% and an effluent value of 20 mg/L, prior to land application. The TKN, NO₃, and P levels were reduced by 96%, 84%, and 88%, respectively. These results were achieved with a septic tank effluent filter and no lagoon aeration. A unique factor of this facility, however, is the batch configuration of the lagoons. While one was fed, the other was idle to allow time for treatment. This leads to long detention times without any additional wastewater entering the treating lagoon. This supports the findings of Vendramelli et al., who state that long periods of isolation improve N removal in lagoons [27]. Applying this method is difficult and expensive for existing facilities that are space-limited.

Facility E had the second lowest concentrations of TN (57.9 mg/L) and the lowest BOD (71.3 mg/L) prior to discharge, and both were comparable to those in domestic wastewater. This was surprising, as the statistical analysis demonstrated that the facilities that slaughtered had significantly higher influent values when compared to those that did not. The lagoon at this facility also had a relatively shorter detention time than the others. Two factors are believed to contribute to this success. This facility had substantial lagoon aeration, both on the surface and in the subsurface. The monthly electricity cost for their aeration is approximately USD 88, but this value is highly dependent on the aeration schedule and lagoon size. This facility also implemented the most blood management among the facilities that slaughtered. With an approximate COD of 400,000 mg/L and a high organic N content, minimizing blood entry into the wastewater substantially reduces the strength of the wastewater [7].

Facility C demonstrates the highest concentrations of TN in the lagoon sample, primarily in the form of organic N and NH₃ (TKN). There are two major contributing factors. The first is the high volume of blood that enters the wastewater at this facility. The wastewater collected from the septic tank was observed to have a red coloration. While a 50% reduction was observed in TN, there was still a substantial concentration of TKN in the lagoon. This facility does not use aeration, which would be expected to achieve further nitrification, improving the progression of the N cycle.

Facility D showed the smallest reduction in TN. In examining other N compounds, it can be observed that TKN did not change between the influent and the lagoon. Breaking

the TKN content down further, organic N decreased while NH_3 increased, leading to a net zero change in the TKN content. The conversion of NH_3 to NO_3 is an aerobic process. Due to the N cycle locking up at the NH_3 stage, adding aeration to this lagoon should be investigated.

There are several options for the improved treatment of meat processing wastewater that must be considered. First, the facility's wastewater must be fully understood. A once-per-year sampling event will not accurately describe the state of a system or lagoon. For those who apply wastewater to land, samples should be taken from the lagoon immediately before or during discharge; otherwise, decisions will be based on inaccurate values. Once the characteristics of the facility-specific wastewater are understood, a typical question is would it be more effective to improve blood and waste collection during operations so that these materials do not enter the wastewater stream to be ultimately land-applied? This option would add costs for disposing of high-strength industrial wastewater, possibly labor, and cleaning supplies, but reduce the level of pretreatment before land application. The other option is to improve pretreatment before land application, which would require greater capital and operational cost but would save resources needed for in-plant blood separation. However, improving pretreatment is complex. Adding aeration will add a major capital cost and require optimization to balance electrical costs and treatment improvements. This includes an improvement in TN reduction as well as BOD. Another example of enhanced pretreatment is maintaining two lagoons, with one receiving the wastewater and the other discharging it, which does not receive fresh wastewater during an extended treatment time. This option, however, can have a significantly higher capital cost when compared to aeration, especially if a geotextile liner is required, but it reduces reoccurring operation costs, such as electricity for aeration. Filters are another option to consider. Filters will improve the BOD and COD in the treatment but incur a capital cost and increase the operational requirements. Operators will need to determine what level of filtration is necessary to meet treatment goals. A reduced pore size will filter out more suspended pollutants, up to the maximum level, but is more susceptible to clogging and requires more labor for maintenance.

In designing a meat processing land application system, the soil's treatment capacity must be considered. This capacity varies greatly depending on the wastewater's characteristics, soil characteristics, and application scheduling. The capacity of the soil can be significant and should not be ignored if it is not saturated and overloaded with organic materials. This capacity should be considered by regulatory agencies in setting permit values. One example of this capacity is the soil's ability to handle FOG. High values of FOG can clog the soil and inhibit wastewater treatment. The high reduction in FOG at all the facilities indicates that this will not be an issue at any of the facilities studied. Reductions in BOD will also be beneficial for land-applied soil and minimize the risk of metal leaching due to low-oxygen environments.

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