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Project Title and Project identification number
Comparison of a Rail-Mounted Automated Power Washer to a Commercial Manual Power Washing Crew in Terms of Cleanliness, Manpower, and Water Usage Efficiency.
#23-046

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Industry Summary

A 2,400 head wean-to-finish barn with two rooms of 1,200 head capacity (196 feet x 50 feet) with 44 pens each was used in the study. A group of nursery pigs were placed in the barn and raised until harvest. The barn was then cleaned, with one room washed using traditional manual power washer methods from a contract service, and the other room cleaned using a railed robotic power washer prototype, followed up with a manual power wash to remove any additional manure (touch-up). The trial consisted of two washing events (August 2023 and February 2024) to compare the efficacy and efficiency of an automated power washer to a manned power-washing crew, based on cleaning time, manpower time, water usage, and cleanliness rate.

In the room washed with the rail robotic power washer prototype, four rails were installed (2 on each side of the room divided by the central hallway) to cover the pen floor and side walls at a maximum height of 10 inches from the slat level. The rail robotic power washer prototype consisted of a trailer head carrying a rotary nozzle connected to a gas power washer. The trailer head was battery powered, and the speed of the trailer on the rail and the speed of rotation of the nozzle could be adjusted. Two different rotary nozzles were tested. The robot power washer with a single rotary nozzle was set to move through the rails at an average speed of 11.0 inches/min, with a nozzle rotation time cycle of 22 seconds (August 2023 data). In the case of the double rotary nozzle, the robotic power washer was set to move at an average speed of 14.8 inches/min, with a nozzle rotation time cycle of 30 seconds (February 2024 data). In both cases, the speed of the trailer head and rotation of the nozzle were adjusted to achieve 2 hits per slat.

Multiple methods were used to evaluate cleanliness (pre-wash, post-wash, and post touch-up): visual assessment, adenosine triphosphate (ATP) measurements to assess organic material, bacterial culture with dip slides, and a reverse-transcriptase real-time PCR (RT-qPCR) for rotavirus detection. There were 12 pens assessed in each room, which were equally spaced throughout the room. Five sites in each pen were assessed: the fencing, floor, wall, waterer, and feeder.

In August 2023 (single rotary nozzle test), total water usage in the robotic power washing room was 8,396 gallons in comparison to 6,211 gallons in the manual power washing room. Total washing time in the robotic power washer room was 22.1 h (13.0 h of robotic washing and 9.1 h of manual touch up washing) in comparison to 10.5 h of manual power washing in the control room. The manual washing labor time in the robotically washed room was reduced 13% (1.4 h), but total washing time was longer by 11.6 h.

In February 2024 (double rotary nozzle data), total water usage in the robotic power washing room was 10,897 gallons in comparison to 7,526 gallons in the manual power washing room. Total washing time in the robotic power washer room was 19.3 h (10.1 h of robotic washing and 9.2 h of manual touch up washing) in comparison to 13.3 h of manual power washing in the control room. In this case, manual washing labor time in the robotically washed room was reduced by 31% (4.1h) with the robot, but overall washing time was longer by 6 h.

Cleaning scores differences before and after washing were significant for each power washer method, at all sites in a pen, and in each testing. The cleanliness trend was from very dirty to clean or very clean. For the robotic power washed room, the post-wash touch-up by the manual power washing team was necessary for the median value to reach the “Very Clean” score.

More bacterial count, rotavirus presence, and ATP levels were found after the washing process for both wash methods. Power washing does not clean the barn, it is solely a means to remove debris and must be followed by a disinfection process. Power washing should be completed to the necessary level to ensure that disinfection can be performed well.

Cleaning expectations of this barn were extremely high, this could explain to some degree the long touch-up process. Robotic power washer cannot easily access the feeders. The washing crew spent considerable time washing the feeders. The number of feeders in the barn will be a limiting factor to the efficiency of the robotic power washer. The barn used for this research has a low pigs/feeder ratio (27 pigs/feeder, doubled 1-hole wet dry feeder). Another limiting factor for the automated power washer is the number of rails and their positioning. In the current study 4 rails were installed in the room. This allowed walls to be washed at a maximum height of 10 inches from the slat level, however, the wash did not cover the central hallway. Additional rails could increase the covered area by the rail power washer, but it would represent additional costs and time of operation.

Although power washing needs at facilities are time and resource intensive, this robotic power-washer prototype does not provide adequate savings in manpower or water usage, so further refinements are needed.

Keywords: Power-washing, robotics, cleanliness, water usage, labor.

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Scientific Abstract

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More bacterial count, rotavirus presence, and ATP levels were found after the washing process for both wash methods. Power washing does not clean the barn, it is solely a means to remove debris and must be followed by a disinfection process. Power washing should be completed to the necessary level to ensure that disinfection can be performed well.

Although power washing needs at facilities are time and resource intensive, this robotic power-washer prototype does not provide adequate savings in manpower or water usage, so further refinements are needed.

Introduction

Barn washing is a key step in ensuring pathogens are not transmitted between cohorts of pigs in the wean-to-finish system. Today this is often done by a manual crew, either contracted or internal to the farm. Contracted crews move from barn-to-barn and increase the risk of disease dissemination which, when considering PRRSV, costs $6.01/head in the nursery and $7.67/head in the grow-finish phase (Kliebenstein et al., 2004).

Manual power-washing can take multiple days to complete as well. A robotic power-washing system could significantly reduce the manpower demand and reduce the need for use of contract washers. This would reduce disease risk and increase farm efficiency. In this study a robotic power washer prototype was compared to a manual power wash against time, water usage, bacterial contamination, and viral presence (rotavirus A).

Objectives

Objective #1: Compare the efficacy and efficiency of an automated power washer to a manned power-washing crew based on cleaning time, manpower time, and water usage (room level data).

Objective #2: Create a cleaning benchmark for swine production facilities through evaluation of visual inspection, quantification of the amount of a ubiquitous swine viral pathogen through real-time PCR, microbiological tools, and an adenosine triphosphate (ATP) bioluminescence meter with the end goal of developing a pass/fail metric (pen level data).

Materials & Methods

A 2,400 head wean-to-finish barn was used for this study. The facility has two rooms of 1,200 head capacity (196 feet x 50 feet), with 44 pens each. A group of nursery pigs were placed in the barn and raised until harvest. The barn was then cleaned, with one room washed using traditional manual power washer methods from a contract service, and the other room, cleaned using a railed robotic power washer prototype followed up with a manual power wash to remove any additional manure (touch-up process). The trial consisted of two washing events (August 2023 and February 2024).

The robotic power washer prototype consisted of a trailer head carrying a rotary nozzle (Figure 1) connected to a gas power washer. The trailer head was battery powered, where speed of the trailer on the rail and the speed of the nozzle rotation could be adjusted.

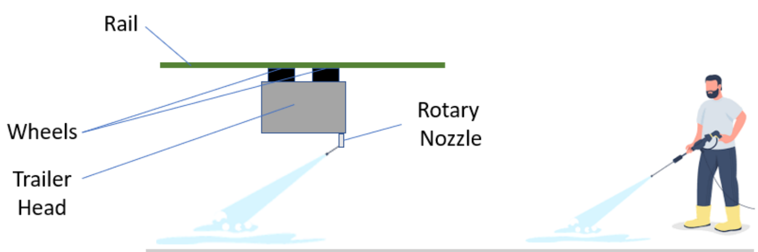

Figure 1. Robotic power washer prototype components (rail, trailer head, wheels, and rotary nozzle).

In the robotic power washer room, four rails were installed (2 on each side of the room divided by the central hallway). In each room side, one rail was installed close to the wall and the other rail was installed close to the central hallway, forming a “U” shape (Figure 2). This allowed walls to be washed at a maximum height of 10 inches from the slat level.

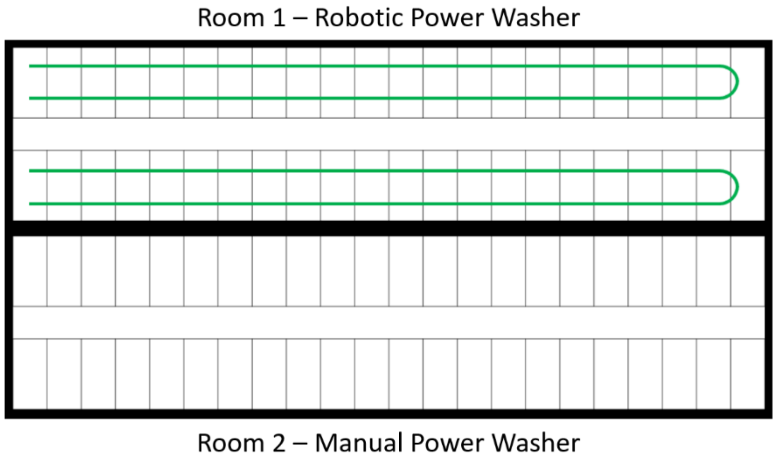

Figure 2. Rail positioning in the robotic power washer room.

For the first washing event (August 2023), the railed power washer prototype had a single rotary nozzle, which was used in the second washing event (February 2024), until it broke with three pens left to be washed on one side of the room. Approximately 43% of the total washing process of the robotic power washer room was washed with the single rotary nozzle. Replacement parts were not easily available and were expensive as well. To finish the washing process, the broken single rotary nozzle was replaced with a double rotary nozzle spare (it was not possible to get spares in time for the single rotary nozzle). For use of the double rotary nozzle, the half room washing time and water usage were doubled to estimate these variables as a room level for the February 2024 testing. The robotic power washer, with a single rotary nozzle, was set to move through the rails at an average speed of 11.0 inches/min, with a nozzle rotation time cycle of 22 seconds. In the case of the double rotary nozzle, the robotic power washer, was set to move at an average speed of 14.8 inches/min, with a nozzle rotation time cycle of 30 seconds. Speed adjustment switches were inconsistent, delivering different speeds with the same settings. So that, speeds were measured and adjusted, to achieve at least two hits per floor slat (previous testing trial recommendations). The throttle was placed at the midway point on the power washing unit (Kohler PA-CH730-3002, 23.5 HP, Wisconsin, USA) for all the testing, delivering approximately between 2,200 to 2,400 PSI at the nozzle level. The pens in each room were soaked prior to power washing overnight. Water was not heated for the power washing process, as is routine in this barn.

Time and water usage were recorded for both washing methods. Water usage was measured using the scale provided on the holding tank and the water gauge in the barn that measures usage in gallons. Load out washing time and water usage were not included in the assessment. Only washing time and water usage spent in the barn were accounted in the assessment (break time for the operator was not included in the washing time). The same person did the manual washing process for both rooms in both washing events.

Multiple methods were used to evaluate cleanliness: visual assessment, adenosine triphosphate (ATP) measurements to detect organic material, bacterial culture with dip slides, and RT-qPCR for rotavirus detection. There were 12 pens assessed in either room, which were equally spaced throughout the room. Pens that were used as a scale and that were at the ends of each row were excluded. Five sites in each pen were assessed: the fencing, floor, wall, waterer, and feeder.

The visual assessment was done to score the apparent cleanliness of the pen and the five sites. A picture was taken of each site in each pen assessed pre-wash, post-wash, and, for the room where the robotic power washer was used, post-touch-up. These pictures were scored separately by two individuals who work in barns daily and are familiar with clean and dirty sites. The individuals were blinded as to the cleaning method of the pen, the pen number, and the time point (pre- or post-wash or post-touchup) at which the picture was taken. A Likert scale was used to score ranging from very dirty, dirty, clean, and very clean. A numerical rating was provided to this ordinal scale and the mean of the two scores calculated for each site in each selected pen.

The ATP measurements were used to detect organic material using Hygiena Ultrasnap swabs and EnSURE luminometer (BioChek USA Corporation, Scarborough, Maine, USA). Samples were taken pre-cleaning (not recommended by the manufacturer), post-cleaning, and post-touch up from the same area of each site assessed. On flat surfaces, approximately 4-inch by 4-inch square surface was swabbed in three different directions using a back-and-forth pattern across the whole space with an Ultrasnap swab. On surfaces without a 4-inch by 4-inch flat surface, surface was swabbed in three directions covering as much surface as possible. The swab was replaced into the swab receptacle, the top broken to release the solution, and the solution squeezed to drain into the area where the swab was at the bottom of the receptacle. The entire receptacle was shaken back and forth for 5 to 10 seconds to soak the swab. The swab was placed into the luminometer, and the reading was recorded. Sample collectors took care not to step on the floor area being sampled during sample collection. Luminometer readings were compared for sites between cleaning time points using non-parametric methods.

The rotavirus testing occurred in a similar manner to ATP swabbing. Rotavirus is a ubiquitous virus of swine and is a reasonable indicator of viral cleanliness as it is expected to be present in most groups of pigs. A polyester swab on a plastic shaft was used to swab each site and then it was placed in a 3 ml tube of phosphate buffered saline. Samples were frozen until all samples were collected and then were dropped off directly to South Dakota State University's Animal Disease Research and Diagnostic Laboratory, where they were extracted and tested using RT-qPCR for rotavirus A, B, and C. Positive and negative results were summarized into percent positivity and cycle threshold values were compared.

Bacterial culture was performed using Sani-Check BC dip slides (Biosan Laboratories, Warren, Michigan, USA). One side has a total coliform agar and the other a total bacteria agar. The slides were placed in contact with the surface for 3-5 seconds. For the waterer and feeder, this was done in segments along the lip of the trough as it was filled with water. For the wall, the slide had to be removed from the top to press it cleanly against the wall. Any slide that was accidentally touched by fingers while removing it from the top, had results discarded. Dip slide vials were then incubated between 34℃ and 36℃ degrees for 24 hours and scored. Scoring was done on a scale of 1 to 7 using the Biosans directions, with score of 1 indicating no growth and 7 being confluent growth.

All scaled data were assessed for normality at each site and time-point using the Shapiro-Wilk statistic. None of the sites assessed had normal data for all three time points. Therefore, the Kruskal-Wallis and Dunn Test were used for the robotic power-washer room that had three time points (pre-wash, post-wash, and post-touch up). A level of significance of 0.1 ($\alpha = 0.1$) was initially used for the Kruskal-Wallis test, and then adjusted using the Bonferroni method to account for the paired data concerns ($\alpha' = 0.03$) when conducting multiple comparisons with the Dunn test. The Wilcoxon signed rank test ($\alpha = 0.1$) was used to compare the manual power-washing room readings (pre- and post-wash). The rank sum test was used to compare cycle threshold readings at different time points for each site (wall, fence, floor, waterer, and feeder) overall, but not as paired data. The positive and negative status of each rotavirus RT-qPCR result was stratified across sampling time and site and evaluated using the Fisher Exact test with a level of significance of 0.1.

Results:

Table 1 illustrates luminometer data. The luminometer ATP readings were higher post-wash and post-touch up on the wall, floor, and feeder in August 2023 and February 2024 when the robotic power washer was used. The post-touch up had the highest readings across all time points at the wall in both time periods and on the floor in August 2023. There were statistical differences in the readings for the wall, floor, fence, and waterer in August 2023 and for the floor, waterer, and feeder in February 2024. When a manual power wash was performed, the luminometer had statistically higher readings in August 2023 and February 2024 on the wall and floor. There were also statistically higher readings on the fence in February 2024, and lower readings in August 2023.

Table 1. Descriptive statistics for the luminometer readings for each site tested across 12-pens per room to compare trends between rooms washed with a robotic power washer and those washed manually.

	Pre-Wash Median (Range)	Post-Wash Median (Range)	Post-Touch Up Median (Range)	P-value
ROOM 1 -Robotic Power Wash				
AUGUST 2023				
Wall	1324.5 (202, 7453)[a]	7079.5 (1988, 8703)[b]	7692 (4984, 9089)[a,b]	0.0001
Floor	958 (254, 4564)[a,b]	3099 (899, 7678)[a]	4779.5 (755,7407)[b]	0.0027
Fence	241 (49, 727)	217.5 (16, 554)[a]	385.5 (121,4034)[a]	0.0824
Waterer	8474.5 (7502, 9334)[a]	8263 (6116, 8807)	7838 (6105, 8890)[a]	0.0233
Feeder	3075.5 (599, 7516)[a]	7891.5 (6745, 8496)[a,b]	5717.5 (1132, 7455)[b]	0.0001
FEBRUARY 2024				
Wall	764 (37, 9295)	2363 (938, 8468)	2076 (558, 5695)	0.52
Floor	292 (30, 5460)[a]	2162 (90, 6864)[a]	741 (346, 3122)	0.0162
Fence	162 (80, 985)	261.5 (10, 1378)	114.5 (34, 1271)	0.5334
Waterer	7506.5 (290, 8531)[a,b]	1558.5 (328, 5345)[a]	2109.5 (926, 6951)[b]	0.0017
Feeder	324 (81, 2301)[a,b]	3758 (646, 8726)[a]	1163 (334, 5537)[b]	0.0003
ROOM 2 - Manual Power Wash				
AUGUST 2023				
Wall	141 (53, 682)	6763 (2175, 8687)		0.0005
Floor	340 (31, 4975)	6486 (3901, 7573)		0.0005
Fence	108.5 (26, 445)	1009 (163, 2508)		0.0024
Waterer	8677 (7450, 9349)	8254.5 (1212, 8682)		0.21
Feeder	3621.5 (300, 7918)	4167 (928, 8875)		0.7334
FEBRUARY 2024				
Wall	2386.5 (111, 8983)	6494.5 (2924, 8459)		0.021
Floor	649 (4, 5158)	6016.5 (765, 32352)		0.0005
Fence	215 (14, 428)	61 (12, 527)		0.0337
Waterer	4871 (1139, 9459)	3377.5 (656, 7799)		0.1294
Feeder	1959 (140, 7471)	1625 (24, 7146)		0.9097

The p-value indicates the Kruskal-Wallis omnibus test probability value (p-value), and the superscript letters indicate pairs that are statistically different evaluated with the Dunn's test using a Bonferroni adjusted level of significance of 0.03 for Room 1. The p-value for room 2 is from the results of the sign rank test.

Table 2 summarizes the bacterial and coliform culture results performed using dip slides. In the room that was cleaned using the robotic power washer, colony counts statistically increased between pre-wash and post-wash on the wall and feeder in August 2023 and on the floor in February 2024 for aerobic bacteria. For coliform bacteria, in both time periods there was a statistically significant increase of coliforms on the wall, floor, fence, and feeder, and on the waterer in February 2024. For the manual power-washed room, significant increases in aerobic bacteria were seen on the floor and feeder in both August 2023 and February 2024 and on the wall in August 2023. As for coliforms, they were increased on the floor, fence, and waterer in both trials.

Table 2. Descriptive statistics for the aerobic and coliform bacteria dip slide readings for each site tested across 12-pens per room to compare trends between rooms washed with a robotic power washer and those washed manually.

Bacterial Culture					Coliform Specific Culture				
	Pre-Wash Median (Range)	Post-Wash Median (Range)	Post-Touch Up Median (Range)	P-value		Pre-Wash Median (Range)	Post-Wash Median (Range)	Post-Touch Up Median (Range)	P-value
ROOM 1 -Robotic Power Wash					ROOM 1 -Robotic Power Wash				
AUGUST 2023					AUGUST 2023				
Wall	4.5 (4, 6)^{a,b}	7 (6, 7)^{a}	7 (6,7)^{b}	0.0001	**Wall**	1 (1, 6)^{a,b}	7 (1, 7)^{a}	7 (3, 7)^{b}	0.0001
Floor	7 (6, 7)	7 (7, 7)	7 (7, 7)	0.1276	**Floor**	2 (1, 7)^{a,b}	7 (6, 7)^{a}	7 (6, 7)^{b}	0.0001
Fence	4 (4, 6)^{a}	4 (3, 6)^{b}	5 (4,7)^{a,b}	0.0107	**Fence**	1 (1, 4)^{a,b}	2 (1, 6)^{a}	3.5 (2, 6)^{b}	0.0001
Waterer	7 (6,7)	7 (5, 7)	7 (5, 7)	0.5071	**Waterer**	7 (5, 7)	6 (2, 7)	6.5 (4, 7)	0.1864
Feeder	6 (4, 7)^{a,b}	7 (6, 7)^{a}	7 (6, 7)^{b}	0.0056	**Feeder**	2 (1, 5)^{a,b}	5.5 (3, 7)^{a}	6.5 (3, 7)^{b}	0.0001
FEBRUARY 2024					FEBRUARY 2024				
Wall	5 (4, 7)	6 (3, 7)	5 (3, 7)	0.2359	**Wall**	3.5 (1, 7)^{a,b}	6 (2, 7)^{a}	6 (6, 7)^{b}	0.0029
Floor	3 (2, 6)^{a,b}	5.5. (4, 7)^{a}	6 (3, 7)^{b}	0.0018	**Floor**	1.5 (1, 6)^{a,b}	5.5 (2, 7)^{a}	6 (6, 7)^{b}	0.0001
Fence	4.5 (2, 6)^{a}	5 (2, 6)^{b}	3 (1, 4)^{a,b}	0.0013	**Fence**	2 (1, 3)^{a,b}	6 (1, 7)^{a}	4 (4, 6)^{b}	0.003
Waterer	5 (4, 7)	5.5 (3, 7)	5.5 (3, 7)	0.7521	**Waterer**	4 (1, 7)^{a}	6 (1, 7)^{b}	7 (5, 7)^{a,b}	0.0042
Feeder	6 (4, 7)	6 (3, 7)	5 (3, 7)	0.1977	**Feeder**	2.5 (1, 7)^{a,b}	7 (2, 7)^{a}	7 (5, 7)^{b}	0.0005
ROOM 2 - Manual Power Wash					ROOM 2 - Manual Power Wash				
AUGUST 2023					AUGUST 2023				
Wall	5.5 (4, 6)	6 (5, 7)		0.0469	**Wall**	4 (1, 7)	5.5 (2, 7)		0.168
Floor	7 (5, 7)	7 (7, 7)		0.0625	**Floor**	3 (1, 4)	7 (6, 7)		0.0005
Fence	4 (3, 5)	5 (5, 7)		0.0039	**Fence**	1 (1, 1)	4 (2, 5)		0.0005
Waterer	7 (6, 7)	6 (5, 7)		0.4531	**Waterer**	4 (2, 7)	6 (4, 7)		0.0332
Feeder	6 (5, 6)	6 (5, 7)		0.1094	**Feeder**	2 (1, 4)	5 (2, 7)		0.0034
FEBRUARY 2024					FEBRUARY 2024				
Wall	4 (3, 7)	4 (3, 6)		0.457	**Wall**	4 (2, 6)	5 (3, 7)		0.1738
Floor	4 (2, 6)	6, (4, 7)		0.0117	**Floor**	2.5 (1, 6)	6 (3, 7)		0.0078
Fence	3.5 (2, 5)	2.5 (1, 5)		0.2363	**Fence**	1 (1, 4)	3 (1, 4)		0.0078
Waterer	5 (1, 6)	4 (3, 6)		0.6445	**Waterer**	2 (2, 4)	5 (2, 7)		0.001
Feeder	4 (2, 7)	6 (4, 7)		0.0293	**Feeder**	4 (1, 7)	4.5 (1, 7)		0.5488

The p-value indicates the Kruskal-Wallis omnibus test probability value (p-value), and the superscript letters indicate pairs that are statistically different evaluated with the Dunn's test using a Bonferroni adjusted level of significance of 0.03 for Room 1. The p-value for room 2 is from the results of the sign rank test.

Rotavirus presence was also evaluated, and the data is presented in Table 3. There was no change in the percent positivity of rotavirus A in August 2023 in the room cleaned with a robotic power washer between sites tested. In February 2024, there was a statistically significant difference in the percent positivity on the wall, floor, waterer, and feeder. The percent positivity increased across cleaning time points in February 2024. In the manual power washed room, there was a difference in percent positivity on the feeder in August 2023 and on the floor and waterer in February 2024. Again, the difference was an increase in percent positivity. As for comparison of cycle thresholds (Ct), which is a proxy for the amount of virus in the sample, there were significant differences in the robotic power washed room in August 2023 and February 2024 on the wall, fence, and waterer. The Ct values increased on the wall, and fence in both months and increased on the waterer in August 2023 and decreased on the waterer in February 2024. The floor and feeder had significant difference in this room in February 2024 as well with the Ct values falling in both situations across cleaning time points. In the manually washed room, there was a significant difference in Ct values found on the fence in both months with a trend of rising Ct values. In August 2023, the feeder also had a significant difference in the Ct values with Ct values falling across the cleaning time points. Increases in Ct values indicate less virus is present and decreases indicate more virus is present.

Table 3. Descriptive statistics for the rotavirus A reverse transcriptase real-time polymerase chain reaction results for each site tested across 12-pens per room to compare trends between rooms washed with a robotic power washer and those washed manually.

Rotavirus A Percent Positivity					Rotavirus A Cycle Threshold Values				
	Pre-Wash # (%)	Post-Wash # (%)	Post-Touch Up # (%)	P-value		Pre-Wash Median (Range)	Post-Wash Median (Range)	Post-Touch Up Median (Range)	P-value
ROOM 1 -Robotic Power Wash					**ROOM 1 -Robotic Power Wash**				
AUGUST 2023					**AUGUST 2023**				
Wall	5 (41.7%)	6 (50%)	4 (33.3%)	0.91	**Wall**	35.35 (34.35, 36.49)[a,b]	37.15 (36.49, 38.38)[a]	37.65 (37.41, 38.39)[b]	0.0071
Floor	9 (75%)	6 (50%)	7 (58.3%)	0.576	**Floor**	37.64 (36.15, 39.09)	37.33 (36.63, 38.22)	36.66 (34.73, 37.69)	0.2618
Fence	83.3%	5 (41.7%)	9 (75%)	0.139	**Fence**	30.74 (27.97, 35.43)[a,b]	36.07 (34.59, 38.5)[a]	37.29 (35.08, 38.65)[b]	0.0003
Waterer	9 (75%)	4 (33.3%)	6 (50%)	0.154	**Waterer**	36.07 (33.57, 37.42)[a]	35.6 (34.59, 37.18)[b]	37.87 (36.84, 39.69)[a,b]	0.0068
Feeder	4 (33.3%)	5 (41.7%)	3 (25%)	0.903	**Feeder**	37.99 (35.35, 38.67)	36.30 (35.56, 37.65)	37.63 (36.84, 39.05)	0.357
FEBRUARY 2024					**FEBRUARY 2024**				
Wall	7 (58.3%)	10 (83.3%)	12 (100%)	0.046	**Wall**	38.98 (34.22, 39.84)[a,b]	34.32 (29.36, 39.34)[a]	35.63 (33.83, 37.36)[b]	0.0197
Floor	3 (25%)	11 (91.7%)	12 (100%)	<0.001	**Floor**	36.43 (35.39, 39.31)[a]	35.70 (31.12, 36.88)[b]	34.17 (30.58, 35.49)[a,b]	0.006
Fence	100.0%	10 (83.3%)	12 (100%)	0.314	**Fence**	37.10 (33.33, 38.48)[a,b]	36.26 (35.62, 39.87)[a]	35.86 (35.02, 37.32)[b]	0.0442
Waterer	5 (41.7%)	11 (91.7%)	8 (66.7%)	0.041	**Waterer**	37.26 (36.37, 37.87)[a,b]	35.21 (34.35, 39.37)[a]	35.06 (32.91, 38.7)[b]	0.091
Feeder	3 (25%)	7 (58.3%)	12 (100%)	0.001	**Feeder**	39.19 (36.74, 39.28)[a,b]	38.14 (34.34, 39.58)[a]	35.94 (33.70, 37.59)[b]	0.0497
ROOM 2 - Manual Power Wash					**ROOM 2 - Manual Power Wash**				
AUGUST 2023					**AUGUST 2023**				
Wall	7(58.3%)	11 (91.7%)		0.155	**Wall**	34.72 (32.30, 39.07)	34.82 (29.7, 37.37)		0.659
Floor	8 (66.7%)	10 (83.3%)		0.64	**Floor**	36.82 (33.66, 39.28)	35.25 (33.94, 37.29)		0.1457
Fence	11 (91.7%)	11 (91.7%)		1	**Fence**	31.39 (28.67, 38.48)	35.51 (33.72, 37.03)		0.0052
Waterer	9 (75%)	10 (83.3%)		1	**Waterer**	36.58 (29.4, 38.36)	35.14 (30.98, 37.18)		0.1128
Feeder	7(58.3%)	12 (100%)		0.037	**Feeder**	37.44 (36.12, 39.31)	35.87 (30.38, 38.09)		0.0012
FEBRUARY 2024					**FEBRUARY 2024**				
Wall	1 (8.3%)	7 (58.3%)		1	**Wall**	38.91 (--,--)	38.55 (34.85, 39.52)		--
Floor	1 (8.3%)	9 (75%)		0.003	**Floor**	38.29 (--,--)	37.76 (36.56, 39.29)		--
Fence	5 (41.7%)	4 (33.3%)		1	**Fence**	38.19 (37.10, 38.29)	38.70 (38.34, 39.09)		0.0286
Waterer	3 (25%)	10 (83.3%)		0.012	**Waterer**	36.96 (36.01, 37.09)	37.16 (35.72, 38.94)		0.75
Feeder	0 (0%)	3 (25%)		0.217	**Feeder**	--	38.77 (37.84, 39.23)		--

The p-value indicates the Kruskal-Wallis omnibus test probability value (p-value), and the superscript letters indicate pairs that are statistically different evaluated with the Dunn's test using a Bonferroni adjusted level of significance of 0.03 for Room 1. The p-value for room 2 is from the results of the rank sum test with a level of significance of 0.1.

Visual assessments were also completed using a Likert scale. Very clean was scored as "1", clean as "2", dirty as "3", and very dirty as "4". Differences were significant for every power washer method, at all sites in a pen, and in each month. The cleanliness trend went from very dirty to clean or very clean (See Table 4) across cleaning stages. For the robotic power washed room, the post-wash touch-up by the manual power washing team was necessary for the median value to reach "Very Clean" or 1.

Table 4. Descriptive statistics for the average visual scoring results from two blinded graders for each site tested across 12-pens per room to compare trends between rooms washed with a robotic power washer and those washed manually.

	Pre-Wash Median (Range)	Post-Wash Median (Range)	Post-Touch Up Median (Range)	P-value
ROOM 1 -Robotic Power Wash				
AUGUST 2023				
Wall	4 (4, 4)^{a,b}	2.5 (1.5, 4)^{a,c}	1.5 (1, 2)^{b,c}	0.0001
Floor	4 (3, 4)^{a,b}	2 (1.5, 3)^{a,c}	1.5 (1, 1.5)^{b,c}	0.0001
Fence	4 (3.5, 4)^{a,b}	2 (1.5, 3)^{a,c}	1 (1, 1.5)^{b,c}	0.0001
Waterer	4 (3, 4)^{a,b}	2.5 (2, 3.5)^{a}	2.25 (1, 2.5)^{b}	0.0001
Feeder	4 (3.5, 4)^{a,b}	3 (2.5, 4)^{a,c}	1.5 (1, 1.5)^{b,c}	0.0001
FEBRUARY 2024				
Wall	3.75 (1.5, 4)^{a,b}	1.5 (1, 2.5)^{a,c}	1 (1, 1.5)^{b,c}	0.0001
Floor	4 (3, 4)^{a,b}	1 (1, 2.5)^{a}	1 (1, 1.5)^{b}	0.0001
Fence	3.25 (2, 4)^{a,b}	1.75 (1, 3)^{a,c}	1 (1, 1)^{b,c}	0.0001
Waterer	2.75 (2.5, 4)^{a}	2.25 (1.5, 3.5)^{b}	1 (1, 2)^{a,b}	0.0001
Feeder	4 (2.5, 4)^{a,b}	2.5 (2, 3)^{a,c}	1 (1, 1)^{b,c}	0.0001
ROOM 2 - Manual Power Wash				
AUGUST 2023				
Wall	4 (1, 4)	1.5 (1, 4)		0.0156
Floor	4 (3, 4)	1.5 (1, 2)		0.0005
Fence	3.75 (3, 4)	1 (1, 1.5)		0.0005
Waterer	3.75 (2.5, 4)	1.5 (1.5, 3.5)		0.002
Feeder	4 (4, 4)	1.5 (1, 1.5)		0.0005
FEBRUARY 2024				
Wall	3.5 (2.5, 4)	1.5 (1, 2)		0.002
Floor	4 (4, 4)	1.5 (1, 2)		0.0005
Fence	3 (2, 4)	1 (1, 1.5)		0.0005
Waterer	3 (2.5, 3.5)	1 (1, 2)		0.0005
Feeder	4 (3.5, 4)	1 (1,1)		0.0005

The p-value indicates the Kruskal-Wallis omnibus test probability value (p-value), and the superscript letters indicate pairs that are statistically different evaluated with the Dunn's test using a Bonferroni adjusted level of significance of 0.03 for Room 1. The p-value for room 2 is from the results of the sign rank test.

In August 2023 (single rotary nozzle test), total water usage in the robotic power washing room was 8,396 gallons in comparison to 6,211 gallons in the manual power washing room. Total washing time in the robotic power washer room was 22.1 h (13.0 h of robotic washing and 9.1 h of manual touch up washing) in comparison to 10.5 h of manual power washing in the control room. The manual washing labor time was reduced 13% in the robotically washed room (1.4 h), but total washing time was longer by 11.6 h.

In February 2024 (double rotary nozzle data), total water usage in the robotic power washing room was 10,897 gallons in comparison to 7,526 gallons in the manual power washing room. Total washing time in the robotic power washer room was 19.3 h (10.1 h of robotic washing and 9.2 h of manual touch up washing) in comparison to 13.3 h of manual power washing in the control room. In this case, manual washing labor time in the robotically washed room was reduced by 31% (4.1h), but overall washing time was longer by 6 h.

Table 5. Washing time and water usage comparison between rooms washed with a robotic power washer and those washed manually.

ROOM 1 - Robotic Power Washer		
AUGUST 2023[1]		
	Labor Time, h	Water Usage, gal
Robotic Washing	13.0	3,012
Manual Touch-Up Washing	9.1	5,384
Total	22.1	8,396
FEBRUARY 2024[2]		
	Labor Time, h	Water Usage, gal
Robotic Washing	10.1	5,679
Manual Touch-Up Washing	9.2	5,218
Total	19.3	10,897
ROOM 2 - Manual Power Washer		
AUGUST 2023		
	Labor Time, h	Water Usage, gal
Manual Power Washing	10.5	6,211
FEBRUARY 2024		
	Labor Time, h	Water Usage, gal
Manual Power Washing	13.3	7,526

[1] *Single rotary nozzle was used during the washing process.*
[2] *Double rotary nozzle half room washing time and water usage were doubled to estimate these variables as a room level.*

Discussion:
Macroscopically, manual power washing was able to create clean rooms in one wash, while the robotic power washed room required a touch-up. Yet, microscopically, no room became clean from power-washing alone, either manually or with the robot. In fact, more bacteria, organic material, and viruses were found after the room was washed.

In these barns, manure and other material are not scraped and are soaked to allow them to easily be removed by a power-washer. When the manure is sprayed, it is likely aerosolized in a fine mist, which would distribute the bacteria and viruses across the area. Clearly, disinfection is critical after a room is washed, regardless of the method used. Assessing cleaning with tools to measure bacterial growth and bacterial and viral presence was not useful as a result.

Setting a cleaning benchmark using an ATP luminescence proved difficult. Readings varied widely across the different sites and, although the barn was washed, it was not cleaned of organic or microbial material. This could impact disinfection. It is not recommended to take measurements prior to cleaning or after disinfection (Ward-Fore, 2023), but measures prior to cleaning were taken to show any reduction in luminosity that occurred. The debris on the swab reduced the bioluminescent reaction and likely provided inaccurate results (Hygiena, n.d.), impacting the ability of the reader to provide an accurate measure. Overall, the readings indicate that there was no reduction in organic material associated with power-washing with ambient water without a cleaner.

Practically, the robotic power washer prototype needs improvements. Currently, a worker must be present during the power-washing period to ensure that the water hose does not get snagged during the washing process. When the hose pulls on the power washer, it can damage the thread to the nozzle and break the piece. Another refinement needed related to this, is the balance of the trailer head in the rail. When the hose pulls, the trailer head inclines to either side of the rail, moving and altering the washing pattern. The double rotary nozzle allowed use of a faster speed of washing and provided better stability of the trailer head on the rail, due to its parallel connection to the hose, in comparison to the vertical hose connection of the single rotary nozzle.

Cleaning expectations of this barn were extremely high, this could explain to some degree the long touch-up process. Robotic power washer cannot easily access the feeders. The washing crew spent considerable time washing the feeders. The number of feeders in the barn will be a limiting factor to the efficiency of the robotic power washer. The barn used for this research has a low pigs/feeder ratio (27 pigs/feeder, doubled 1-hole wet dry feeder). Another limiting factor for the automated power washer is the number of rails and their positioning. In the current study 4 rails were installed in the room. This allowed walls to be washed at a maximum height of 10 inches from the slat level, however, was not enough to cover the central hallway. Additional rails could increase the covered area by the rail power washer, but it would represent additional costs and time of operation.

Although power washing needs at facilities are time and resource intensive, this robotic power-washer prototype does not provide adequate savings in manpower or water usage, so further refinements are needed. No power washing method cleans the barn, it is solely a means to remove debris and must be followed by a disinfection process. Power washing should be completed to the necessary level to ensure that disinfection can be performed well.

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