Enhancing Air Quality and Toxic Chemical Removal Through Sustainable Orchard Wood Utilization in Vermifiltration Systems

Final Report

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Prepared for:

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and
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Preface

Perca, Inc., in collaboration with the Western Center for Risk Management Education at Washington State University, submits this final report as part of a contract project with the Washington State Department of Ecology (Contract No. C2400111). The project was conducted under the guidance of the Agricultural Burning Practices and Research Task Force (Ag Task Force), which operates under the direction of Washington State Department Ecology (Ecology) as established by the Washington Clean Air Act (Chapter 70A.15 RCW). This study contributes to the goal of researching alternative methods to reduce or eliminate emissions from agricultural burning.

Acknowledgments

We thank Jerad Ashbeck for his support in wood sourcing, chipping, and lab system operations. Appreciation is also extended to Anne Nelson for assistance preparing the grant application, and to the orchardists who contributed their time, insights, and feedback to inform this research.

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1. Executive Summary

The need for sustainable alternative methods that reduce air pollutants generated by burning orchard tear-out debris has been voiced by multiple stakeholders and government agencies for decades. The reality that it remains an ongoing issue underscores the complexity in the resolution of the challenge. It may be that the persistence of this single core ecological air quality issue veils multiple secondary factors. If so, then the overall solution to the reduction of atmospheric contaminants from orchard debris burning might best be ameliorated by various disposal strategies incentivized by economic, aesthetic, and educational benefits.

The Washington State Department of Ecology (Ecology) provided funds for Perca, Inc. to pursue an alternative approach that eliminates the production of air contaminants by orchard debris combustion along with the simultaneous benefit of wastewater treatment and generation of a soil amendment. Previous studies funded by Ecology have detailed methods, materials, and economics of chipping orchard debris as an alternative to burning. Perca's innovation builds on this initiative by on-site processing of wood chips to include transportation and installation of this resource in a wastewater vermifiltration system (VFS).

The efficacy of apple orchard wood chips in the VFS wastewater treatment was evaluated in a specially designed microcosm Rapid Assay Vermifiltration (RAV) system created by Perca, Inc. Conventional and non-conventional wastewater parameters all were reduced to levels that equaled or surpassed those attained by standard wastewater treatment systems. The data acquired with the RAV system and subsequent analysis is detailed in this final report.

Systems-oriented industrial symbiosis is a central focus of the Perca VFS as illustrated above. In addition to contributions in the reduction of air and water pollutants, spent wood chips from the VFS have the potential to improve certain soil ecosystems as an amendment. With all these community and business spheres involved in this multivariate approach in an alternative to orchard debris disposal there is the additional benefit of ecological and economic education that sustains rather than degrades the environment.

2. Background

Agricultural waste management presents significant challenges, particularly in mitigating air pollution from open-air burning and finding sustainable uses for organic byproducts. Our study is focused on the use of vermifiltration to treat wastewater with a simultaneous incorporation of associated environmental enhancements through industrial symbiosis. The Perca Vermifiltration System (VFS) has demonstrated high efficiency in the reduction of conventional (biological oxygen demand, total dissolved solids, and total suspended solids) and nonconventional (polychlorinated biphenyls and per- and polyfluoroalkyl substances) pollutants in municipal and industrial wastewater. In addition, economic feasibility, market potential, and scalability are assessed, both for the Perca VFS as well as the adjacent synergistic environmental industries on which the system depends.

This research builds directly upon a previous Ecology-funded grant completed in 2023 (Ecology Contract No. C2200108) that explored the feasibility of using coarse chipped orchard tear-out wood (>½ in) as a filtration substrate in large-scale agricultural and industrial wastewater systems. That project demonstrated technical success and market interest in coarse media applications, especially for dairies and food processors, and laid the foundation for a broader model of Agricultural Industrial Symbiosis: using the waste from one industry as input for another to reduce waste and enhance sustainability through cycles of use and reuse. The current study represents a logical progression of that work, focusing on orchard wood fines – the byproduct of coarse orchard chipping operations – as a potential medium for treating domestic and toxic wastewater streams at a moderate loading application rate. This focus not only addresses the management of finer material, which previously lacked a defined end-use, but also strengthens the case for full-spectrum utilization of chipped biomass as a tool for both air quality improvement and water treatment innovation.

3. Purpose

The design and implementation of the Perca vermifiltration system (VFS) is rooted in the principle of industrial symbiosis, reflecting the interdependence found in natural ecosystems. Rather than serving a singular function, the system is built to integrate pre-treatment and post-treatment pathways that generate multiple environmental and economic benefits. A primary focus of this project is the reuse of orchard waste, specifically apple tree tear-out debris, in a sustainable and cost-effective way to reduce air pollution associated with agricultural burning.

This applied research project aimed to evaluate the technical, economic, and environmental feasibility of utilizing leftover chipped wood fines from fruit orchard tear-outs as a carbon-rich substrate in a vermifiltration system for wastewater treatment. A common disposal method of spent apple trees in the Pacific Northwest has been to pile orchard pullout debris and reduce it by burning, which negatively impacts regional air quality and the soil quality of the burn site. As an alternative, onsite chipping of this material reduces those impacts while generating a primary input for the Perca VFS. The project examined the effectiveness of toxic substance removal, specifically polychlorinated biphenyls (PCBs), and the viability of repurposing treated substrate as a low-risk soil amendment.

By coupling orchard biomass reuse with water purification, the project presents a closed-loop solution that reduces air pollution from agricultural burning, enhances water quality, and promotes regenerative uses of organic waste. The study also evaluated the treatment performance of the vermifiltration system using apple wood fines as the primary organic media, comparing its pollutant removal capacity to that of conventional substrates. This work supports broader Department of Ecology goals by demonstrating how nature-based systems – leveraging wood chips and worms – can advance air quality, water purification, and material circularity. For each of these outcomes, the study evaluates cost, scalability, stakeholder input, and environmental performance to support future implementation across agricultural and wastewater sectors.

4. Orchard Tear-Out Debris Sourcing and Chipping

4.1. Overview and Objectives

This task involved the systematic collection of cost and operational data related to the transformation of apple orchard tear-out debris into suitable organic media (OM) for use in Perca's vermifiltration systems. Specific objectives included quantifying the costs of sourcing, transporting, chipping, and screening apple wood from Eastern Washington orchards, evaluating both the logistical feasibility and market landscape for long-term substrate supply, as well as obtaining representative samples for laboratory testing.

4.2. Material Acquisition

A local orchard near Benton City, WA, USA was accessed to harvest apple orchard wood from a randomly selected debris pile created during a routine non-trellised orchard tear-out process in early Spring of 2024. Approximately 600 lb of debris was selected as a representative sample that consisted of branches and trunk pieces with an average length of 4 feet. Material that ranged 3–6 inches in diameter was used to ensure an adequate wood to bark ratio based on current standards for vermifiltration bedding which resulted in approximately 450 lb of usable raw material shown in figure 1.

Figure 1. Raw material from a trellised orchard used to create chipped organic material for vermifiltration testing.

4.3. Chipping and Screening Processing

Following field selection, usable wood portions were manually separated, and non-organic contaminants such as plastic irrigation tubing and trellis wire were removed. While this material came from a non-trellised orchard, where trees grow without support infrastructure, foreign material removal was still labor- and time-intensive. In contrast, trellised orchards utilize posts, tensioned wires, and other structural components to support high-density planting systems. These systems, though efficient for fruit production, introduce substantially more foreign debris into the biomass stream, requiring significantly greater effort and cost to prepare wood for chipping and reuse. Figure 2 provides an example of the types of foreign material encountered during this acquisition process. The economic implications of this additional processing burden are further examined in the economic analysis section of this report.

Figure 2. Orchard tear-out debris with embedded foreign material encountered during wood chipping process.

The raw wood was transported to a processing site, where it was chipped using industrial equipment, including the Morbark Eeger Beever 1621X. This commercial-grade chipper effectively handled the dense apple wood, producing a heterogeneous mix of chips and fines suitable for downstream separation and sizing. Because the chipping process yields a broad range of particle sizes – from coarse, bark-covered chunks to small, splinter-like fines – a screening step was necessary to isolate the specific fraction appropriate for vermifiltration media. The chipper used in this study was similar in scale and function to that used in the initial vermifiltration study, and the screen used (½-inch square mesh) was identical, allowing us to closely replicate the fines produced as a byproduct in the first study (Ecology Contract No. C2200108). Figure 3 shows the chipping equipment alongside the manual screen used to separate the usable fines from oversized material.

Figure 3. Industrial chipper processing orchard tear-out wood (left) and manual screen used to separate fines (<½ inch) from oversized material for use as vermifiltration media (right).

Chipped material was screened to isolate fines less than ½ inch in diameter, which was the target size for this study. Chips above ½ inch in diameter have been shown in previous study to be useful in high solid vermifiltration applications and therefore were discarded in this study to determine the usefulness of fines in moderate and toxic vermifiltration applications. Screening was performed using a 24” x 21” box screen with ½-inch square mesh. Figure 4 displays the screened output, showing both the retained fines and the discarded larger chips, with a U.S. quarter for scale.

Figure 4. Oversized wood chips (>½ inch) discarded from the screening process (left) and retained fines (<½ inch) used as substrate media in vermifiltration testing for this study (right).

The process yielded approximately 33% usable fines by mass from raw chipped material. During one representative trial, 424 pounds of orchard debris with foreign objects already removed produced 140 pounds of fines and approximately 55 gallons (0.27 yd^3) of usable substrate. The remaining material was primarily large chips not used in this study and loss associated with chipping and screening. Since VFS systems are measured by volume, all estimates must be adjusted accordingly, as material mass varies due to factors such as moisture content and density. These parameters of the orchard tear-out are representative of standard chipping material at approximately one year after the tear-out process. Using this volume and mass, the calculated material density was 514 lb/yd^3, or approximately 0.26 tons/yd^3. Table 1 shows the yields of each step of culling material for the final OM used for the VFS testing.

Table 1. Mass (lb) of material obtained through the chipping process

Process Step	Start Mass (lb)	Usable Mass (lb)	Usable %
Tear-out pile culling	600	450	75%
Foreign material removal and loss	450	424	94%
Chipping, screening, and loss	424	140	33%

4.4. Transport and Delivery

Following chipping and screening, OM fines were transported to the Perca facility in Walla Walla, WA. Transportation costs were tracked per ton-mile, with current estimates averaging $2.25/ton for 100-mile transport. Seasonal availability and drying logistics were documented to optimize supply timing and avoid degradation.

Data from selection, transportation, and chipping were used to estimate the costs of labor and equipment, calculate the tons of usable chips per ton of orchard debris, as well as other relevant factors to evaluate the feasibility of orchard tear-out debris as a viable vermifiltration substrate.

5. Laboratory Testing

5.1. Purpose and Study Design

The successful expansion of orchard tear-out debris into a value-added substrate media for vermifiltration hinges on the ability of apple wood media to perform similarly or better than existing standard organic media. Figure 5 shows the two OM used for bench-scale testing in a visual comparison.

Figure 5. Apple wood chip fines (left) and traditional, conifer-based organic media (right) used as substrate materials in bench-scale vermifiltration testing.

Due to vermifiltration's widespread use in domestic wastewater treatment, contaminated domestic wastewater was selected as the influent source to evaluate both conventional and toxic contaminant removal performance in Perca's vermifiltration systems. To ensure relevance to real-world conditions, wastewater was collected from an anonymous domestic source known to contain measurable levels of PCBs. Prior to use, the wastewater was pre-screened through a 250 µm filter to remove large debris that could obstruct the precision irrigation openings of the test system. The screened wastewater was transferred into a sanitized intermediate bulk container (IBC) tote and transported to the Perca VermiTech Innovation Center (VIC) for testing. Upon arrival, the wastewater was transferred into stainless steel storage containers and held in a temperature-controlled cold room at 4°C to limit microbial degradation during the holding period between RAV system refills. This storage protocol ensured influent consistency and preserved contaminant integrity for accurate performance assessment. Figure 6 shows the transfer of wastewater into the storage tanks following initial collection and screening.

Figure 6. Transfer of screened wastewater from the IBC transport container (left) into the facility cold storage tanks used to preserve wastewater at 4°C prior to dosing into the RAV systems (right).

The laboratory testing was conducted using two identical Rapid Assay Vermifiltration (RAV) systems, shown in figure 7, designed to mimic the structure and function of a full-scale vermifiltration unit. One system was filled with chipped apple orchard fines, while the other served as a control and was filled with traditional organic media. Both systems were irrigated through a calibrated delivery system designed to distribute influent water evenly across the media surface. Water was applied in five-second spray cycles every hour, simulating a batch-fed application rate of approximately 3.68 gallons per day. This dosing rate corresponds to a scaled version of the full-scale loading rate of approximately 5.5 gallons per square foot per day, adjusted for the size and conditions of the bench-scale test units.

Figure 7. Rapid Assay Vermifiltration (RAV) systems used for bench-scale testing containing traditional organic media (left) and apple wood fines (right).

Testing was conducted over a 9-week period to allow for the development of the biologically active zone formed by earthworm activity, known as the drilosphere, and the establishment of an acclimated microbial community. The RAV systems were maintained in stable environmental conditions inside the VIC, where temperature was held at 21°C and a natural diurnal/nocturnal light cycle was observed. A dim light remained on overnight to discourage earthworm escape. Earthworm containment was successful, with only minor losses recorded: eight in the apple wood system and seven in the traditional media, both within the accepted norm for bench-scale tests. To support consistent system performance and maintain contaminant integrity, batches of pre-screened, refrigerated wastewater were transferred weekly into the RAV source tank to replenish supply and preserve cyclic flow throughout the study. Figure 8 shows the transfer setup used to load wastewater into the source tank from cold storage.

Figure 8. Transfer setup used to load refrigerated wastewater from cold storage into RAV source tanks.

We assessed the wastewater treatment capability of the apple wood chip fines by measuring the removal efficiency of total suspended solids (TSS) and biological oxygen demand (BOD) as indicators of conventional contaminant reduction, and PCBs to evaluate toxic chemical remediation potential. Influent wastewater was collected from a single source and batch, with characterization data showing TSS and BOD concentrations had a standard deviation of 6–15 mg/L and a coefficient of variation of 10%. This consistency in influent quality supported the use of single-sample influent testing. Effluent from each RAV system was collected every three weeks, for a total of three sampling events, and composited before being sent to certified independent laboratories for analysis.

5.2. Total Suspended Solids Analysis

Total Suspended Solids (TSS) removal was highly effective within the apple wood media system. Samples 1 and 2 exhibited complete removal (100%), while sample 3 achieved a reduction of 76.1%, yielding an average TSS reduction of 92.0%. A paired t-test between influent and effluent concentrations confirmed this removal was statistically significant (p = 0.0074), indicating strong performance by the vermifiltration system using apple wood fines. The TSS treatment results are illustrated in figure 9, which shows influent and effluent concentrations across samples 1–3 within the apple wood system.

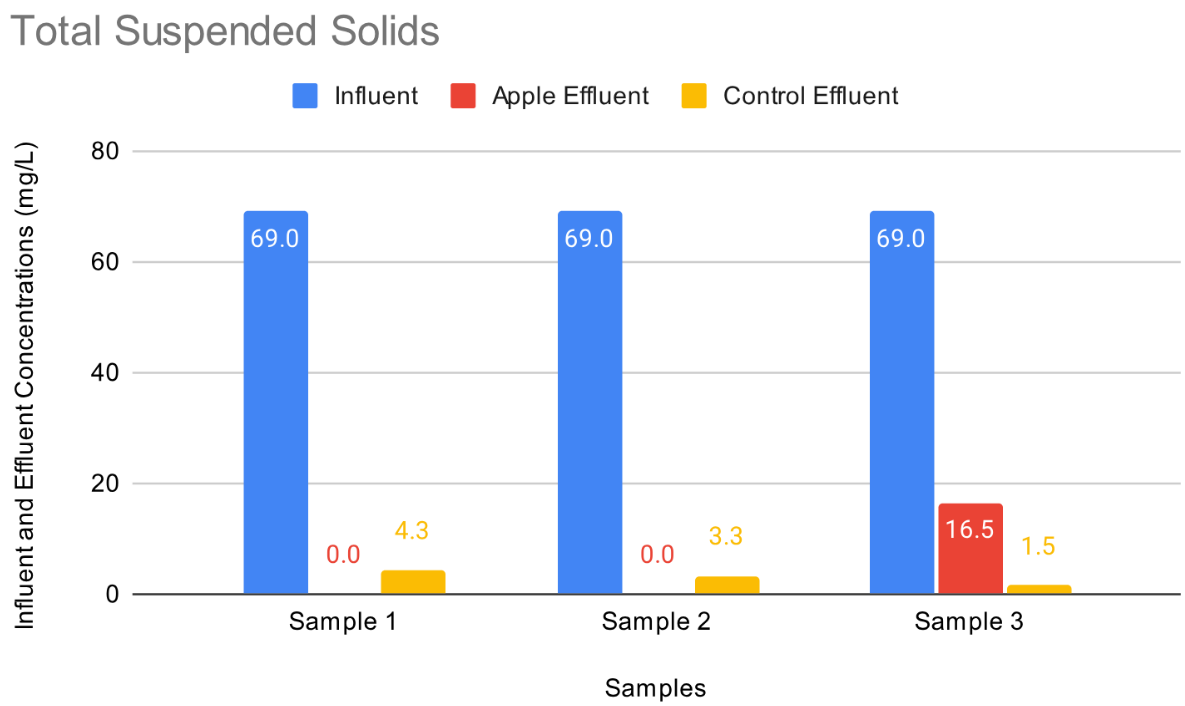

Figure 9. Influent and effluent total suspended solids (TSS) concentrations across Samples 1–3 for both apple wood and control media.

In the control system, TSS removal was also substantial, with reductions of 93.8%, 95.2%, and 97.8% across samples 1–3, respectively, and an overall average reduction of 95.6%. A paired t-test between influent and effluent concentrations for the control system also confirmed statistically significant removal ($p = 0.00015$). This is slightly higher than the apple wood system's average removal but not statistically significantly different, indicating that both apple wood and traditional media are effective at treating TSS within a vermifiltration system. A more detailed comparison of these results is provided in Section 5.5.

5.3. Biological Oxygen Demand

The apple wood-based system demonstrated substantial efficacy in reducing biological oxygen demand (BOD). Removal efficiencies ranged from 70.0% to 93.1% across the three samples, with an average of 80.3%. Despite variability, all results showed meaningful treatment, and a paired t-test confirmed the reduction was statistically significant ($p = 0.0070$). This supports the capability of apple wood media to facilitate robust microbial degradation of organic matter in wastewater. Figure 10 depicts the influent and effluent BOD concentrations for each sample treated with the apple wood system.

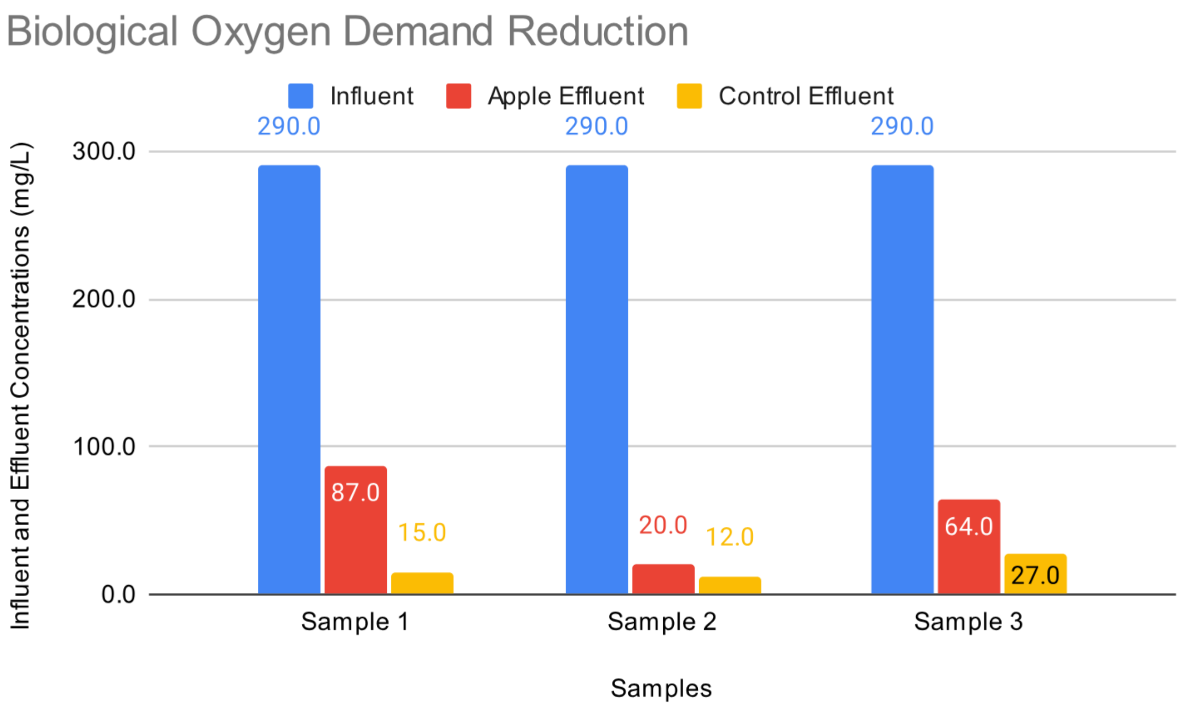

Figure 10. Influent and effluent biological oxygen demand (BOD) concentrations across Samples 1–3 for both apple wood and control media.

In the control system, BOD removal was even higher, with efficiencies of 94.8%, 95.9%, and 90.7% across the three samples, and an overall average reduction of 93.8%. A paired t-test between influent and effluent concentrations in the control system confirmed the removal was statistically significant ($p = 0.00028$). Although slightly higher than the apple wood system, the difference is not statistically significant, indicating that both systems effectively reduce BOD within a vermifiltration setup. A more detailed comparison of these results is provided in Section 5.5.

5.4. Polychlorinated Biphenyls

5.4.1. PCBs in Water

Apple wood media also achieved effective removal of polychlorinated biphenyls (PCBs). While samples 1 and 2 saw reductions greater than 93%, performance dipped in sample 3 to 67.6%, resulting in an overall average reduction of 85.5%. Despite this variability, a paired t-test revealed a statistically significant difference between influent and effluent concentrations ($p = 0.011$), confirming the system's effectiveness in reducing toxic chemical loads. Figure 11 shows influent and effluent PCB concentrations within the apple wood treatment.

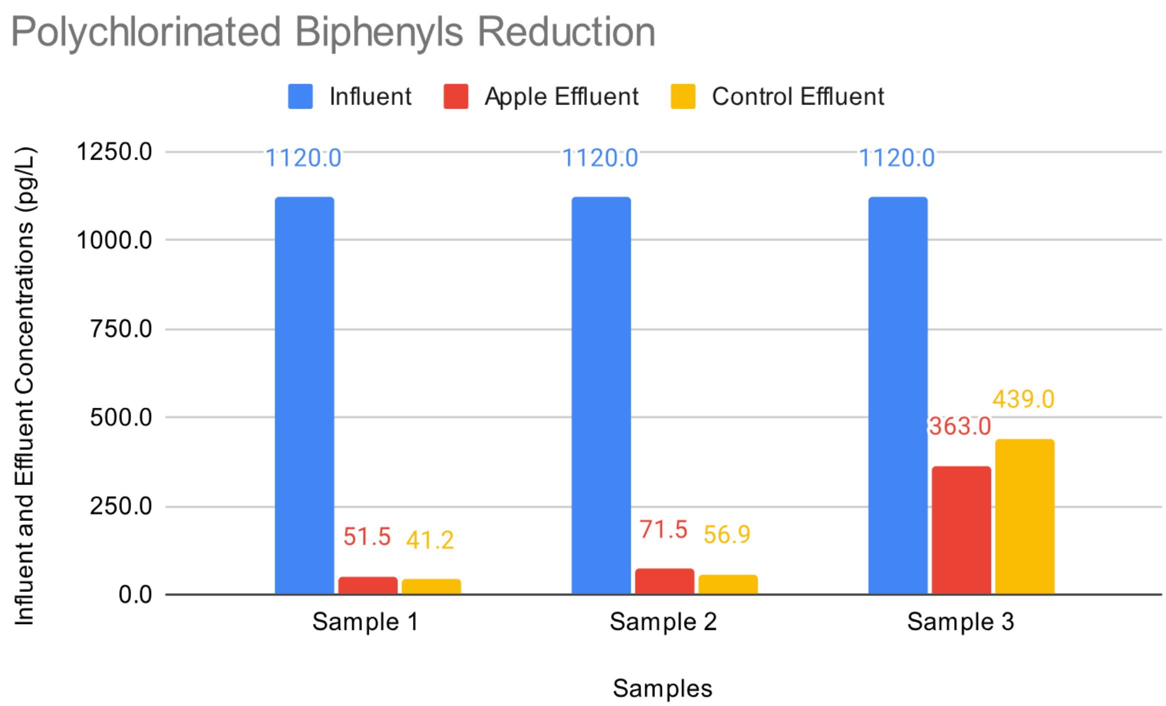

Figure 11. Influent and effluent polychlorinated biphenyls (PCBs) concentrations across Samples 1–3 for both apple wood and control media.

In the control system, PCB removal was similarly high, with reductions of 96.3%, 94.9%, and 60.8% across samples 1–3, averaging 84.0% overall. A paired t-test between influent and effluent concentrations in the control system confirmed this removal was statistically significant ($p = 0.0186$). The average removal was slightly lower than the apple wood system, though the difference is not statistically significant, indicating that both systems are effective for PCB reduction in a vermifiltration context. A more detailed comparison of these results is provided in Section 5.5.

5.4.2. PCBs in Substrate

Following the conclusion of the experimental period, a composite sample of the vermifiltration substrate was collected and analyzed for total PCBs in an independent, certified laboratory. The apple wood substrate showed a concentration of 112 ng/kg, while the pine-based organic media (OM) contained 116 ng/kg. While these values are low in absolute terms, they illustrate a form of bioaccumulative behavior whereby hydrophobic contaminants like PCBs accumulate in the filter substrate driven by the compound's physicochemical affinity for organic carbon and the low aqueous solubility of PCB congeners.

Despite this tendency for accumulation, the PCB concentrations detected in the substrate are orders of magnitude below regulatory thresholds. Washington State's unrestricted land use soil cleanup level for PCBs is set at 1.0 mg/kg, while the state's designation for Washington-only PCB (WPCB) dangerous waste is 2.0 mg/kg. Federal disposal regulations under the Toxic Substances Control Act (TSCA) apply only at levels exceeding 50 mg/kg. In contrast, the substrate values observed in this study (0.000112–0.000116 mg/kg) are nearly a million times lower than these regulatory action levels. Table 2 below summarizes key regulatory thresholds for PCBs in Washington State and under federal regulations.

Table 2. Regulatory thresholds for polychlorinated biphenyls (PCBs) in Washington State and under federal TSCA guidelines, shown in both mg/kg and ng/kg for comparison

Regulatory Context	Limit (mg/kg)	Limit (ng/kg)	Source
WA unrestricted land use soil cleanup level	1.0	1,000,000	WAC 173-340-740
WA-only PCB dangerous waste designation	2.0	2,000,000	WA Dept. of Ecology, 2021
Federal TSCA hazardous waste handling requirement	50.0	50,000,000	EPA, 2023

5.4.3. End Uses for PCB Contaminated Substrate

The results from laboratory analysis indicate that the level of PCB accumulation in the spent vermifiltration substrate is sufficiently low to permit broad environmental use without regulatory restrictions. This opens a diverse array of practical, beneficial end uses for the material, especially in contexts where organic content, microbial activity, and soil-building capacity are valued. Because the substrate retains the biological richness developed during filtration – including a thriving microbial community and earthworm-influenced soil structure – it presents not only a non-hazardous byproduct, but a valuable biological input.

In low-contamination contexts such as those observed in this study, the spent substrate can be directly applied to land as a soil amendment or blended into compost intended for non-food production systems. Ideal applications include municipal landscaping projects, mine reclamation, non-food agricultural soil amendment, and more. In these settings, the substrate contributes structure, moisture-holding capacity, and a diverse microbiome – all without introducing problematic contaminant loads. Compost producers may also integrate the material into their feedstocks, provided product quality and labeling guidelines are followed.

For situations involving higher levels of PCB contamination, which may arise from long-term use in heavily polluted treatment streams, the end-use decision shifts from disposal to potential strategic deployment in soil remediation. Because the biology within the substrate has been conditioned to PCB exposure, it may exhibit enhanced degradative potential for PCBs under the right environmental conditions. The microbial populations and enzymatic pathways present could facilitate in situ bioremediation, particularly in marginal or legacy-contaminated soils where introducing adapted organic material can accelerate breakdown processes. Alternatively, the substrate may be used in containment zones, brownfields, or treatment cells where its sorptive and microbial characteristics are harnessed in a controlled system.

Whether repurposed for compost, land application, or remediation, vermifiltration substrate represents not a waste product, but an ecologically functional material whose potential is shaped by both its origin and its treatment history. Its rich biological profile and sorptive capacity make it valuable across a range of reuse pathways, particularly as part of circular waste strategies. To support responsible and informed reuse, ongoing research at Perca – through collaborations with research partners – is investigating the long-term behavior of PCBs in vermifiltration systems, including the potential for further accumulation or gradual biological degradation during extended operation. Although PCBs are chemically persistent, the unique synergy of microbes and invertebrates within the substrate may enable slow transformation under favorable conditions. This work will help define safe media replacement intervals, refine end-use guidance, and further validate the environmental safety and regulatory viability of vermifiltration-based treatment systems. As these insights evolve, they will expand flexible, high-value reuse options that maximize both environmental and economic benefits.

5.5. Comparison of Apple Wood and Control OM Media

To evaluate the relative effectiveness of the apple wood substrate compared to a traditional organic media (OM) control, we analyzed the percentage reduction across all three parameters. A t-test comparing the percent reduction values between the two media yielded no statistically significant differences for any parameter: TSS ($p = 0.73$), BOD ($p = 0.17$), and PCBs ($p = 0.62$). These results indicate that the treatment performance of apple wood is statistically equivalent to that of conventional OM media. The comparative data are summarized in figure 12, which displays percent reductions for apple and control across all samples.

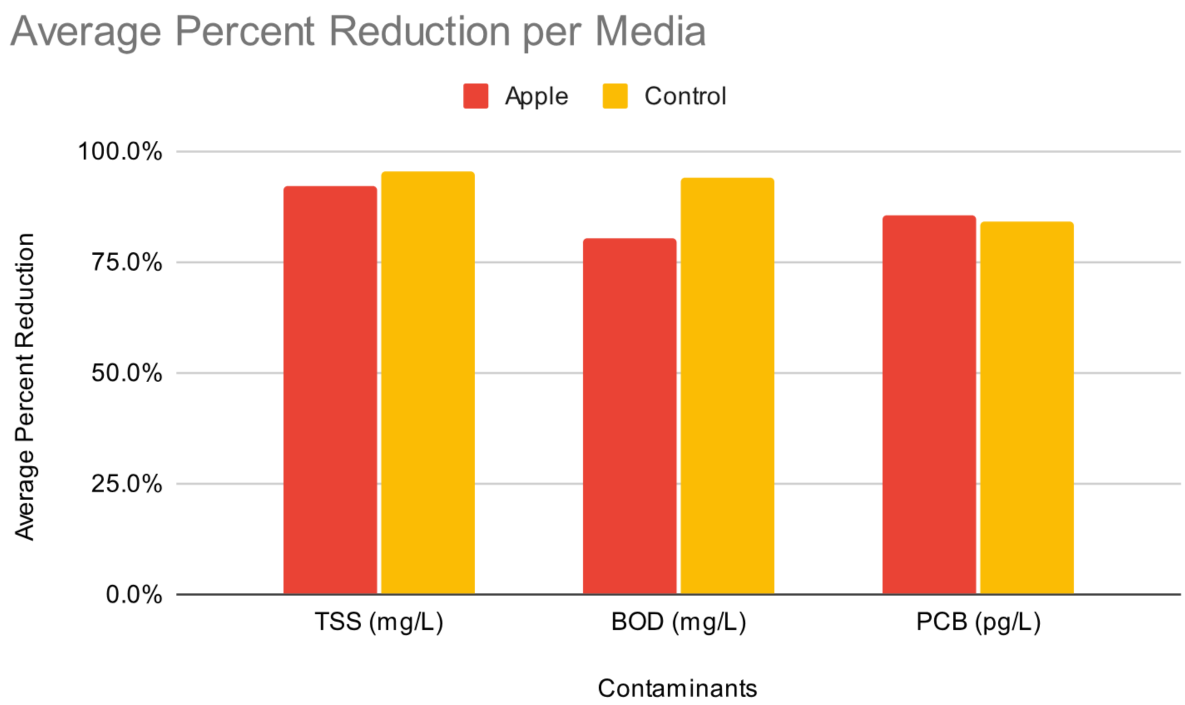

Figure 12. Average percent reduction of total suspended solids (TSS), biological oxygen demand (BOD), and polychlorinated biphenyls (PCBs) for apple wood and control media across all samples.

5.6. Data Analysis Summary

To evaluate the effectiveness of the two OM sources, we conducted paired t-tests to compare influent and effluent concentrations for each parameter within each media type, and unpaired tests to compare the reduction efficiencies between the apple wood and control systems. Both substrates demonstrated statistically significant reductions ($p < 0.05$) in TSS, BOD, and PCBs, confirming their effectiveness in wastewater treatment within a VFS. However, no statistically significant differences ($p > 0.05$) were found when comparing the percent reductions between the two OM sources. This indicates that wastewater treatment performance was comparable regardless of whether apple or traditional OM was used. These findings suggest that apple orchard tear-out fines can serve as a viable, value-added alternative to conventional substrates in vermifiltration systems. Figure 13 summarizes the average reduction percentages for each parameter across treatments, offering a visual overview of system-wide performance.

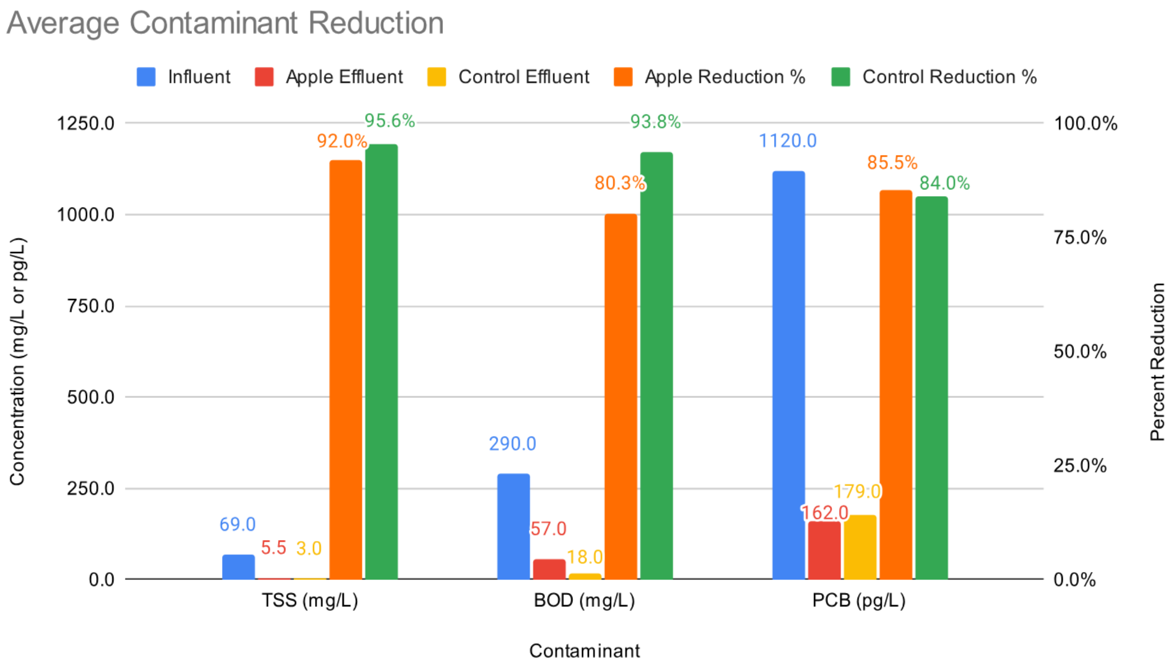

Figure 13. Average influent and effluent concentrations and percent reductions for TSS, BOD, and PCBs across apple wood and control media.

5.7. Post-Trial Media and Biological Observations

At the conclusion of the 9-week testing period, several distinct physical and biological differences were observed between the apple wood and traditional pine-based media in the RAV systems. Visually, the effluent from the apple wood system appeared noticeably darker in color than the pine control, suggesting greater suspended organic content not measured through TSS and BOD, or may be attributed to leaching of naturally occurring extractives, which can include color-bearing compounds such as tannins and polyphenols. A visual comparison of effluent from the apple wood and traditional pine-based media RAV units are shown in figure 14.

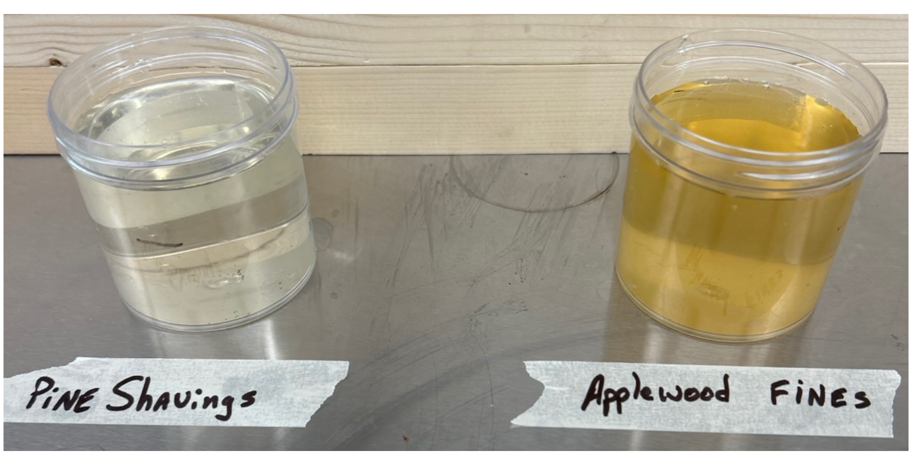

Figure 14. Effluent from RAV systems using traditional pine-based media (left) and apple wood fines (right).

Compaction of the media beds was also measured as settling occurs from the effects of gravity through the life of a VFS requiring operational maintenance such as occasional media addition. Pine media in the RAV unit compacted by approximately 9.5 in, while the apple media compressed by 7 in, both within the expected range for vermifiltration systems. However, differences in moisture and texture were notable. The pine media appeared drier and less saturated than apple fines, indicating better drainage characteristics, while the bottom third of the apple media was heavily compacted, water-saturated, and nearly devoid of worms suggesting reduced oxygen availability and limited habitability in that zone. In contrast, the bottom third of the pine media remained well-aerated and supported the majority of its earthworm population.

Earthworm distribution and population dynamics also varied markedly between the two systems. The apple wood system supported a robust and highly active worm community, with both adult and juvenile earthworms present in high numbers – particularly concentrated in the upper third of the media as shown in figure 15.

Figure 15. Upper third of the apple wood media bed at the conclusion of testing, showing high earthworm activity and visible saturation compared to traditional media.

Fruit fly presence was also noted at the surface of the apple media, consistent with higher levels of surface organic activity. The pine system, by contrast, had a more modest worm population primarily composed of adults concentrated in the lower third of the media bed. The lower population is likely due to the known antimicrobial properties of pine, which may have suppressed reproduction or initial colonization. Some early mortality was observed in both systems during the first week, attributed to the absence of cover material per standard protocol to avoid cross-contamination; however, the apple system showed significantly greater reproduction and population rebound over time. These biological and physical observations reinforce the conclusion that apple wood media is not only functionally viable for contaminant removal but also highly supportive of earthworm health and reproduction under vermifiltration conditions.

6. Economic Feasibility

6.1. Cost Drivers: Sourcing, Chipping, Transport

Perca's economic feasibility study confirmed that the use of chipped apple orchard tear-out wood as a substrate in vermifiltration systems is influenced heavily by the origin of the material and the processing pathway. Chipping orchard debris is not widely used as a management tool due to intensive cost and limited markets for chipped orchard material. Historically, it is an insufficient financial alternative for orchard debris disposal if not subsidized (Washington State Department of Ecology, 2010). Utilization of chipped apple orchard debris as value-added VFS media requires specific handling and processing of raw material to produce suitable chips for OM media. Among constraints on economic feasibility in the pursuit of this goal are usefulness of trellised versus non-trellised orchard tear-out material, size specifications of chippable orchard material (noted above), and required mechanization and labor. The cost of orchard debris handling per acre is defined in this study as all processing activities prior to activities used to convert raw debris material into a value-added product, including piling, foreign material separation (e.g., trellis wire), and chipping preparation. Other cost variables such as transport, chip production, and screening are consistent regardless of tear-out origin. Drawing on interviews with three Washington State apple orchardists, data collected from chipping wood to use in the VFS bench-scale study, and a literature review, we captured labor requirements, hard costs, and yields associated with chipping apple orchard debris into usable VFS media. Table 3 summarizes the economics of chipping trellised versus non-trellised apple orchard tear-out debris.

Table 3. Economic analysis of the cost of chipping trellised and non-trellised apple orchard tear-out debris

Cost and Yield Metric	Trellised Orchards	Non-trellised Orchards
Cost of orchard debris handling per acre	$12,500.00	$2,500.00
Tons of wood per acre	8.5	21
Yield of 3 inch or larger	50%	75%
Usable tons of wood per acre	4.25	15.75
Cost of wood per ton	$2,941.18	$158.73
Trucking cost $/ton	$2.25	$2.25
Chipping cost $/ton	$65.00	$65.00
Wood chips cost per ton	$3,008.43	$225.98
Cost per cubic yard	**$1,719.10**	**$129.13**

Pricing for traditional VFS media is currently at $37.50 per cubic yard of OM. Pricing for apple wood chips calculated in this study is substantially higher than traditional media, posing a financial hurdle for the alternative use of orchard debris as VFS media. This elevated cost stems from the labor-intensive nature of orchard removal, the absence of established infrastructure for processing orchard debris at scale, and the limited ability of existing mechanized systems to handle foreign materials such as trellis wire, plastic clips, and irrigation components. These contaminants require manual separation, adding cost and time to the processing pathway. Among apple sources, trellised orchard systems further increase costs due to two primary factors: (1) foreign material removal is more intensive and labor-dependent due to denser use of trellis infrastructure; and (2) trellised trees yield smaller, more fragmented branches due to growth constraints along wire supports. These branches frequently fall below the 3-inch diameter minimum required for chipping under current VFS media specifications, reducing the proportion of usable wood per acre. This lower yield translates to significantly higher per-ton processing costs for trellised systems. Future work assessing the potential of smaller-diameter branches or pruning debris as VFS media could support more practical and scalable integration of chipped apple orchard debris into filtration systems.

Reducing the cost of chipping and improving chipping efficiencies remains an important task to improve the integration of orchard debris into novel markets. However, opportunities for novel OM for VSF media are growing as the market for wood chips has become highly competitive due to declining lumber production driven by environmental regulations, wildfires, and reduced timber availability. High demand from large-scale commercial production of paper, cardboard, and pressed wood products further limits available OM supply thus increasing chipped orchard debris market opportunities.

6.2. Market Viability for Apple Wood Fines

Viability of chipped orchard tear-out debris as VFS media depends on the scalability and potential market of apple wood chips as an OM for substrate material. While there is no established commercial market for chipped orchard wood fines as filter media, several trends suggest an emerging opportunity. Declining sawmill output has created supply gaps in wood chip markets, which is increasing demand for alternative biomass sources. At the same time, regulatory pressure to reduce reliance on synthetic or chemically treated materials is driving interest in organic alternatives. Early feedback from agricultural and environmental clients also indicates a growing preference for regionally sourced, low-impact filtration materials that align with sustainability goals while interviews with orchardists indicate a desire to find a sustainable alternative to open air burning that is cost and labor effective.

6.3. Value-Added Revenue from Vermicompost

Perca's VFS units generate vermicompost, a biologically enriched byproduct that is gaining traction in regenerative agriculture and land restoration. Although its economic impact was not monetized in this phase, literature and market comparisons suggest that compost can retail from \$25 to \$150 per cubic yard, depending on nutrient profile and market. For Perca, this represents a potential offset to the high costs of wood media and offers a second revenue stream that can improve the overall system economics. Further development of the compost market, including branding, certification, and pilot distribution to local farms and vineyards, will be a focus for future commercialization planning.

6.4. Feasibility of Scaling Orchard Wood Utilization in VFS

Based on market projections for Perca's vermifiltration system, market penetration within the Pacific Northwest (Washington, Oregon, and Idaho, USA) is projected to grow at a compound annual growth rate (CAGR) of 113.45%, reaching 9.57% of the market over the next five years. Using calculated market growth projections in addition to standard Perca VFS proposals, table summarizes the projected cubic yard and tonnage requirements for organic media (OM) to support VFS deployment from 2025 to 2029; in this study, chipped apple orchard debris is evaluated as a potential OM source that could provide a value-added outlet for orchard tear-out material. Scaling is expressed as a percentage of one standard full-scale in addition to the DemO$_2$ trials, which are not projected to increase in number. Alternative VFS markets are not included in these projections indicating further opportunities outside Perca systems for chipped orchard tear-out debris as OM for VFS.

Table 4. Wood chip market projections for Perca VFS for 2025-2029

Year	Deployment Model	OM (yd³)	OM (US tons)
2025	4 $DemO_2$ Trailers	57	15
2026	60% of 1 Standard System + 4 $DemO_2$ trailers	3,693	949
2027	128% of 1 Standard System + 4 $DemO_2$ trailers	7,814	2,009
2028	265% of 1 Standard System + 4 $DemO_2$ trailers	16,117	4,143
2029	539% of 1 Standard System + 4 $DemO_2$ trailers	32,724	8,412
Total		**60,406**	**15,528**

To evaluate the potential scalability of sourcing OM from apple orchards across Washington, we analyzed statewide orchard tear-out data (Table 5). According to USDA's National Agricultural Statistics Service, Washington has approximately 173,000 acres of apple orchards. Orchardist interviews and crop profiles suggest an orchard lifespan of 30 to 35 years, resulting in an average annual tear-out rate of 3.1% – or approximately 5,400 acres removed each year. Actual removal of orchards varies depending on consumer preference of varieties, tree production, age, and more. Actual removed acres per year will vary significantly.

Table 5. Estimated annual availability of orchard tear-out debris from Washington State apple orchards, including calculated yields of usable wood fines based on chipping efficiency and material density

Metric	Value	Source
Total WA apple orchard acreage	173,000	USDA NASS
Avg. tear-out rate per year (%)	3.1%	Orchard interviews + literature
Acres removed per year	5,354	Calculated
Tons of debris per acre	8.5	Orchard interviews
Total tear-out mass per year	45,512	Calculated
Usable yield from chipping (%)	33%	Field data
Usable fine wood per year (tons)	15,028	Calculated
Tons per cubic yard	0.26	Field data
Usable volume per year (yd³)	**58,460**	**Calculated total**

With a conservative estimate of 8.5 tons of debris per acre based on multiple orchardist interviews, total annual tear-out material in the state may reach 45,500 tons. Applying the observed 33% yield rate of usable chips from usable debris found in our chipping study and ignoring marginal loss from foreign material removal, this equates to approximately 15,000 tons of usable chip fines per year. Based on our measured density of 0.26 tons per cubic yard, the total usable volume equates to approximately 58,500 cubic yards per year. This volume is sufficient to support both demonstration-scale and full-scale deployment of Perca's VFS systems through 2029 and beyond depending on realistic orchard tear-out debris availability. With proper logistics and feedstock planning, current statewide tear-out rates offer a sustainable, long-term supply of OM. Seasonal availability, logistics, and competition with other biomass markets (e.g., mulch, paper, energy) also factor into feedstock planning.

6.5. Orchardist Feedback and Input on Scalability

Orchardist interviews provided critical insight into how the vermifiltration system could scale within the operational and economic realities of orchard management. Decision-making around orchard removal was reported to be primarily economics-driven – based on the profitability of fruit varieties and declining yield – rather than dictated by tree age. Orchardists noted that pruned wood and small limbs were not viable sources of material due to their size and high levels of contamination. Usable feedstock was typically only available during full orchard or block removals, which generally occur in the fall and winter.

On average, orchardists estimated that approximately 8.5 tons of debris were generated per acre during removal events, with roughly 2.8 tons per acre deemed usable after sorting. However, separating this material required significant manual labor to remove embedded wire, cut to size, and prepare for chipping. One orchardist estimated the additional labor cost for processing usable wood from trellised orchards at up to $15,000 per acre, making the task prohibitively expensive without structural support.

To make the project scalable, orchardists emphasized the need for field-side processing services such as mobile chipping and wire separation equipment. They also highlighted the importance of aligning seasonal orchard removal with processing availability through coordinated contracting support. Additionally, growers suggested that economic incentive structures – especially during early implementation phases – would be necessary to test logistics, evaluate true costs, and ensure participation.

6.6. Comparative and Competing Technologies

Perca's DrilO$_2$ vermifiltration system sets itself apart in the evolving wastewater treatment market through its flexible and integrative design. The system is highly scalable, making it suitable for a wide range of wastewater volumes – from small agricultural operations to larger industrial facilities. Its customizable substrate media, including the innovative use of apple wood fines, allows for enhanced removal of organic pollutants, nutrients, and even persistent contaminants. Additionally, the system can be seamlessly integrated with other nature-based solutions, such as constructed wetlands and biochar filtration units, creating a multi-barrier approach that improves treatment performance and ecological benefits.

While conventional treatment technologies such as activated sludge and membrane filtration continue to dominate much of the market, they are increasingly challenged by rising energy costs, complex maintenance requirements, and heavy reliance on chemicals or synthetic polymers. These factors are creating a window of opportunity for emerging, nature-based alternatives that offer lower operational costs, simplified maintenance, and improved sustainability. Technologies like anaerobic membrane bioreactors, electrocoagulation, and modular treatment units are gaining attention, but many remain capital-intensive or lack the low-footprint, decentralized appeal of systems like $DrilO_2$.

In this competitive landscape, solutions that emphasize low-maintenance operation, energy efficiency, and adaptability to varying waste streams are well-positioned to lead the next wave of innovation. Perca's $DrilO_2$ system not only aligns with these emerging priorities but also provides a differentiated value proposition by transforming organic waste into a functional component of its treatment process. As regulatory and market pressures continue to favor sustainable and decentralized water management, Perca stands to gain significant traction as a leader in the next generation of wastewater treatment technologies.

7. Air Quality Impact

7.1. Air Pollution due to Orchard Debris Burning

Open-air burning of orchard tear-out debris remains a widespread practice in Washington State, particularly in fruit-producing regions like the Yakima Valley and Central Washington. This method of agricultural waste disposal emits a harmful mix of air pollutants – including particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and ammonia (NH_3) – that contribute to environmental degradation and pose serious health risks. Rural communities situated near burn sites are especially vulnerable to these emissions, which have been linked to respiratory and cardiovascular conditions.

The Washington State Department of Ecology has identified outdoor burning as a major contributor to air pollution, emphasizing its role in elevated $PM_{2.5}$ levels and urging the adoption of cleaner, non-burning alternatives to protect public health and improve air quality (Washington

State Department of Ecology, n.d.-a; Washington State Department of Ecology, n.d.-b). While agricultural burning is permitted year-round under specific regulatory conditions, November emerges as a peak month for orchard debris burning due to its timing after harvest and its typically cooler, wetter conditions that minimize wildfire risk.

Air quality monitoring data from November 2024, illustrated in Figure 16, shows a pronounced decline in air quality across Washington State. Measurements from dozens of Department of Ecology stations reveal a clear spike in AQI levels from November 5 to November 15, with many locations reaching the “Moderate” (yellow), “Unhealthy for Sensitive Groups” (orange), and even “Unhealthy” (red) categories. This deterioration in air quality aligns with the seasonal timing of orchard tear-out and burn activity. In contrast, baseline AQI readings during periods with minimal or no burning generally fall within the “Good” (green) range – typically below 50 – highlighting the direct impact of agricultural burning on ambient air quality.

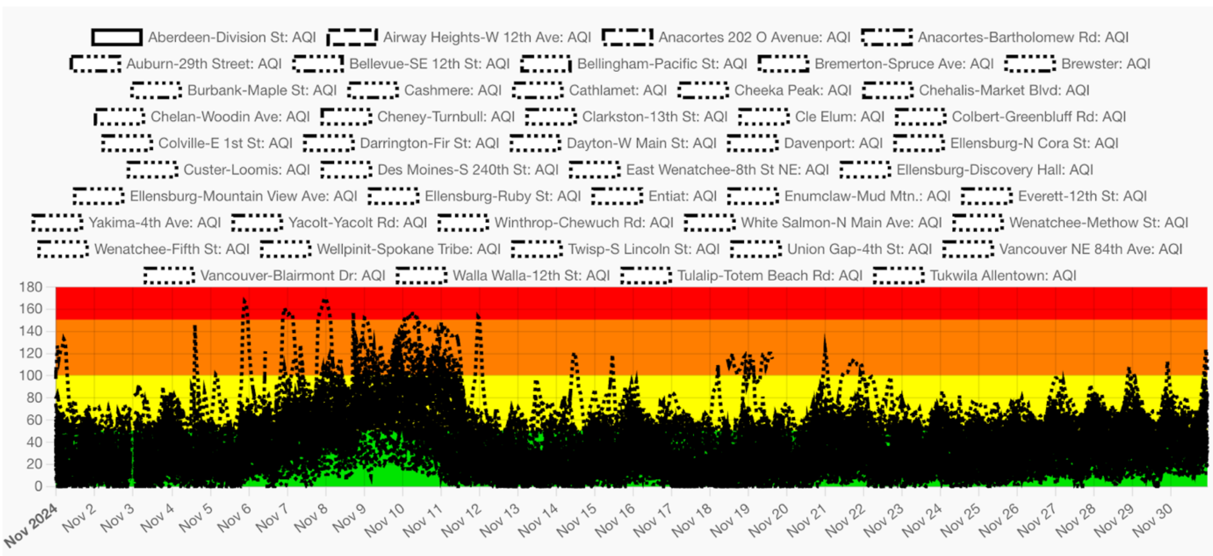

Figure 16. Air Quality Index (AQI) data from Washington State monitoring stations during November 2024, showing elevated pollutant levels coinciding with peak orchard burning activity.
Source: https://enviwa.ecology.wa.gov/

This data supports the rationale for transitioning toward alternatives such as chipping orchard debris for use in organic wastewater treatment media. Doing so could significantly reduce seasonal spikes in air pollution and protect the health of rural residents, especially those with respiratory vulnerabilities. In response to these concerns, the Perca Vermi-Filtration System (VFS) offers a sustainable alternative by repurposing chipped apple orchard debris as an organic medium (OM) for wastewater treatment. This approach not only addresses waste management challenges but also significantly reduces pollutant emissions associated with traditional burning methods. By diverting biomass from open-air combustion to beneficial reuse, the VFS contributes to improved air quality and aligns with the state's environmental and public health objectives.

7.2. Emissions Reductions from Burning Avoidance

Between 2025 and 2029, Perca VFSs are projected to utilize approximately 60,500 cubic yards, or 15,500 tons, of chipped apple orchard tear-out material as organic media, effectively diverting it from open-air burning. The air quality benefits of this diversion can be quantified using emission factors published by the Washington State Department of Ecology. Their most recent update to the 2020 Washington Comprehensive Emissions Inventory (2024, Publication #20-02-012) outlines pollutant emissions associated with the open burning of various orchard types. Table 6 provides emission factors for open burning of apple orchard debris and cherry and pear orchard debris for comparison. Differences between orchard tear-out where entire trees are burned versus pruning debris are not provided.

Table 6. Burn emission factors for three orchard woods in lb per ton of material consumed (from updated 2020 Washington Comprehensive Emissions Inventory)

Emission	Apple (lb/ton)	Cherry (lb/ton)	Pear (lb/ton)
CO	42	44	44
NO_x	5.2	5.2	5.2
PM_{10}	3.9	7.9	7.9
$PM_{2.5}$	3.7	7.4	7.4
SO_2	0.1	0.1	0.1
VOC	3	8	8
NH_3	12.52	12.52	12.52

Source: Washington State Department of Ecology. *Washington Comprehensive Emissions Inventory (WCEI), Publication #20-02-012.* Updated 2024.

Diverting apple orchard tear-out and pruned material from burn piles into a chip resource used in vermifiltration avoids burn emissions in direct proportion to the size of the vermifiltration bed needed to treat wastewater. Using calculated market projections for total cubic yards needed in vermifiltration systems and conversion factors for volume to mass ratios of ideal wood chips found in our chipping process in this study (0.26 tons per cubic yard of media), this equates to over 62,000 cubic yards, or more than 16,000 tons of orchard debris converted into a value added product rather than burning for next 5 years from the projected implementation of Perca VFSs. Table 7 shows an extended projection of emissions (in lb) savings from using chipped orchard tear-out as OM in VFS equaling more than 1,100,000 total lb of projected emissions saved from 2025-2029. This projection does not account for emissions savings from the remaining approximate 67% of chipped material that was not used in the VFS but will still be utilized in other applications, since it has already been processed.

Table 7. Extended projected emissions (lb) savings from utilizing apple orchard debris fines as vermifiltration media for Perca vermifiltration systems 2025-2029

Year	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	NH_3
2025	614	76	57	54	1	44	183
2026	39,874	4,937	3,703	3,513	95	2,848	11,886
2027	84,368	10,446	7,834	7,432	201	6,026	25,150
2028	174,012	21,544	16,158	15,330	414	12,429	51,872
2029	353,298	43,742	32,806	31,124	841	25,236	105,317
TOTAL	**652,167**	**80,744**	**60,558**	**57,453**	**1,553**	**46,583**	**194,408**

Figure 17 visualizes the compound air quality benefit associated with scaling the Perca VFS across the Pacific Northwest.

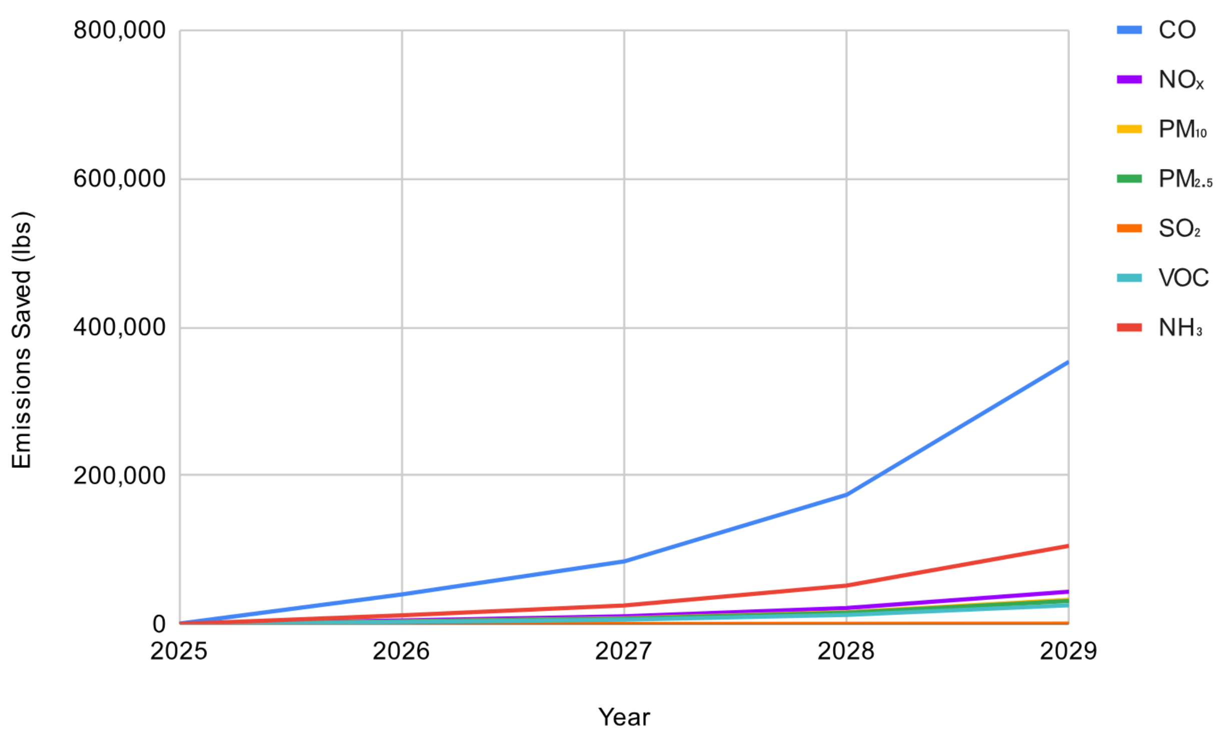

Figure 17. Extended projected emissions (lb) savings from utilizing apple orchard debris fines as vermifiltration media for Perca vermifiltration systems 2025-2029.

7.3. Other Impacts and Limitations

7.3.1. Theoretical Sufficiency and Real-World Variability in Feedstock Supply

While the potential environmental benefits of substituting burning with chipping are substantial, feedstock availability remains a key constraint. Based on current agricultural trends and data further Washington State generates approximately 45,500 tons of apple orchard tear-out debris annually. However, due to foreign material removal, chip size specifications, and screening loss, only approximately 33% of this is usable as vermifiltration fines, equating to approximately 15,000 tons or 58,500 cubic yards per year. This projected supply is not fixed, however, and is shaped by dynamic factors as described by orchardists interviewed for this study. Primary drivers of orchard tear-out stems from market-driven varietal changes, orchard production, and other dynamic factors that may result in excess or limited apple wood-based OM for VFSs. Simultaneously, the volume of OM required for VFS deployment is highly variable and depends on implementations of new systems, locations of new systems, influent quality (which influences the frequency of bed replacement), and more. These variabilities imply that while vermifiltration systems can offset significant emissions, widespread adoption requires flexible sourcing strategies and possibly supplemental media types.

7.3.2. Air Pollution Avoidance from Alternative Chip Fraction Utilization

The remaining 67% of chipped material, classified as larger than ½ inch, is not considered waste, but rather not the focus of this study. Previous studies through Washington State Department of Ecology funding (Ecology Contract No. C2200108) indicate successful utilization of coarser chips in high-solid or industrial-strength vermifiltration systems, where increased void space and aeration are advantageous. These chips can also be used in alternative value-added end uses including, but not limited to, soil amendment, mulch, biochar feedstock, wood smoking products, and more.

Leveraging these alternative streams maximizes material circularity and reduces waste, aligning with the principles of industrial symbiosis and further avoiding air pollution. Because this larger fraction is derived from the same original biomass as the fine fraction, its avoided emissions potential can be reasonably estimated using proportional analysis. If 33% of the biomass (15,500 tons) avoids over 1.1 million pounds of emissions when used instead of burned, then full utilization of the remaining 67% would avoid an estimated 2.2 million additional pounds of pollutants. In total, diverting all chipped orchard wood – both fine and coarse fractions – from burn piles to productive use would eliminate more than 3.3 million pounds of emissions over five years. This reinforces the critical role that full-spectrum utilization of orchard tear-out material can play in reducing environmental harm, advancing sustainable agriculture, and meeting Washington State's air quality goals.

7.4. Air Pollution Analysis Summary

The Perca VFS initiative presents a compelling air quality solution, capable of eliminating over 1.1 million pounds of harmful pollutants through the redirection of orchard tear-out debris fines from burn piles into high-functioning OM for VFSs. While supply limitations and processing labor represent real constraints, a diverse range of alternative applications for larger chip fractions bolsters both the environmental and economic case for orchard chipping. A systemic shift toward chipping and away from open burning can help Washington State meet its air quality, waste reduction, and climate resilience goals.

8. Education and Outreach

The outreach and education strategy for this project prioritized building awareness, cultivating support among orchard and agricultural stakeholders, and sharing findings through both professional and community-facing platforms. The following subsections detail how each element of the outreach deliverables was achieved through targeted engagement, presentations, and public education efforts.

8.1. Outreach to Fruit Grower Associations

To encourage early buy-in from the agricultural community and explore the practical potential of diverting orchard tear-out debris from burning toward beneficial reuse in vermifiltration systems, the project team conducted targeted outreach to key orchardist-based organizations across Washington State. In fall 2024, the team reached out to the Washington Tree Fruit Association (WTFRC) to request a presentation slot at their Annual Meeting; although the 2024 agenda was full, the team was invited to consider presenting at the December 2025 meeting. In November 2024, the team also contacted the organizers of North Central Washington Tree Fruit Days, seeking to participate in the January 2025 meeting, but did not receive a presentation invitation. The project also engaged with the Columbia Club, a long-established grower group, to discuss orchard tear-out processes and the feasibility of supplying chipped material for vermifiltration applications. Although a meeting opportunity was available in March 2025, the project ultimately prioritized direct orchardist interviews at that time to collect critical data on tear-out practices.

Through these engagements, the team shared the project's objectives – namely, evaluating chipped apple orchard wood as a viable organic medium for wastewater treatment in vermifiltration systems – and discussed key considerations such as material handling, costs, and compatibility with grower priorities like sustainability, regulatory compliance, and soil health. While formal presentations were not delivered, these conversations helped raise awareness about the potential for innovative reuse of orchard biomass and created important connections for future collaboration and outreach.

8.2. Conference Presentations

In 2025, the team presented the project's research and findings at two major national conferences, helping fulfill the commitment to share results with academic, public, and private stakeholders. The first presentation took place at the Waste to Worth Conference, held April 7–11 in Boise, Idaho. Featured on the Air Quality and Greenhouse Gas Emissions Track, this presentation focused on the system's potential to reduce air pollutants and GHGs through the diversion of orchard wood from burning and its use in vermifiltration. The second presentation was delivered at the Air & Waste Management Association Annual Conference, June 9–12 in Raleigh, North Carolina, under the Agricultural Waste Reuse and Sustainable Products for Food Systems Track. This venue emphasized the broader sustainability implications of the system, including pollutant removal data and integration with circular agricultural systems. At both events, the team engaged in discussions with representatives from universities, state agencies, consulting firms, and agricultural innovation groups, expanding interest in the application of vermifiltration with regionally available wood substrates.

8.3. Public Education and Community Integration

Throughout the project period, the team incorporated key messages and findings into existing Perca outreach efforts and educational programming. This included onsite tours of the vermifiltration system, community-facing exhibits, and presentations at events such as the Walla Walla Return to the River Festival, municipal environmental fairs, and local sustainability gatherings. These efforts expanded the project's reach beyond academic and technical circles to include orchardists, wastewater operators, municipal decision-makers, regulators, high school and university students, and general audiences. By embedding the project's goals and outcomes into outreach platforms, the team highlighted both the scientific findings and the broader environmental implications of transitioning away from burning toward beneficial uses of biomass, demonstrating how collaboration with agriculturalists can drive sustainable innovation and rural-urban systems integration.

9. Conclusion

Perca, Inc., with funding from Ecology, has proposed, tested, and analyzed a plausible resolution to the persistent impacts of burning orchard debris. The incorporation of industrial symbiosis concepts expands the reach of ecological benefits to pre- and post-operational achievements of the Perca vermifiltration wastewater system. The focus of this final report for Ecology is the redirection of orchard debris from a mere disposal problem that diminishes air quality to a resource that improves water and soil quality driven by a combination of economic, aesthetic, and educational gains.

Laboratory testing demonstrated that apple orchard tear-out fines perform comparably to conventional organic media in the removal of total suspended solids, biological oxygen demand, and polychlorinated biphenyls from wastewater. All influent-to-effluent reductions were statistically significant ($p < 0.05$), and no statistically significant differences were found between the apple wood and control media, indicating apple wood can serve as a viable drop-in replacement for traditional materials.

The environmental impact of this approach extends beyond water treatment: the diversion of chipped orchard biomass from open burning to vermifiltration media resulted in an estimated avoidance of over 1 million pounds of air pollutant emissions over a five-year projection. Moreover, the resulting substrate meets all regulatory thresholds for land application, offering viable end uses ranging from compost integration to soil remediation.

Importantly, the study also engaged stakeholders across sectors, fostering early interest and laying the groundwork for future collaboration. Through conference presentations, direct engagement with grower associations, and integration into community education events, the project fostered meaningful cross-sector dialogue – supporting policy, practice, and public understanding around sustainable biomass reuse. These outreach efforts were essential in raising visibility for vermifiltration and orchard wood reuse and will be critical in future implementation phases.

Despite these gains, economic and logistical barriers remain. One of the most significant obstacles to realizing the value-added potential of using orchard debris as vermifiltration media is the limited awareness among growers and decision-makers of its combined financial and environmental benefits. In particular, the high labor costs associated with separating usable wood, especially in trellised orchards, and the lack of processing infrastructure present meaningful economic hurdles. Emerging technologies such as semi-automated wire removal, mobile chipping units, and improved screening systems offer promising pathways to reduce these costs over time. Expanding education around cost offsets such as avoided burn fees, potential subsidies, emissions reductions, or vermicompost revenue will be critical to overcoming these barriers and enabling broader adoption.

Future research will continue to evaluate the long-term behavior of PCBs in the substrate and the economic optimization of orchard chip processing. Additionally, research could explore the feasibility of incorporating orchard tear-out debris with diameters smaller than the current 3-inch standard, which would expand usable material from trellised systems and potentially include pruned biomass. This would further improve utilization rates and broaden the economic opportunity for orchard operators. Taken together, the evidence confirms that vermifiltration offers not only an environmentally sound alternative to burning, but a scalable and circular solution aligned with Washington State's air quality and waste reduction goals.

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