13 (2022) 200063

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Performance analysis and life cycle assessment of acrylic concrete structures for rainwater harvesting

Azadeh Bolhari [a,*], Daniel I. Castaneda [b], Jay H. Arehart [a], Shelby J. Tillema [a]

[a] *Department of Civil, Environmental, and Architectural Engineering. University of Colorado Boulder, 80302, Boulder, Colorado, United States*
[b] *Department of Engineering, James Madison University, 22807, Harrisonburg, VA, United States*

ARTICLE INFO

Keywords:
Acrylic concrete
Rainwater harvesting
Mechanical testing
Water quality
Life-cycle assessment

ABSTRACT

This study investigates the viability of acrylic concrete (AC) tanks as an alternative rainwater harvesting (RWH) material through structural, water quality, and global warming impact data – focusing on material reuse and availability for sustainable communities. The mechanical testing evaluated the flexural strength of AC mixtures made with varying dosages of acrylic paint, Portland cement, and sand. The results identified mechanically viable AC mixtures and the largest flexural strength value was observed in the mixture with 20% Portland cement and 80% acrylic paint by weight at 28-days with a modulus of rupture of 266 psi. The water quality tests measured the water quality of tanks built with AC mixtures and the results identified the presence of total and fecal coliforms, bis(2-ethylhexyl) phthalate, and benzoic acid. Measured inorganic compounds were below the World Health Organization guidelines for drinking water. The life cycle assessment of different AC mixtures as compared to other common RWH tank materials indicated that the AC RWH tank performs the best when acrylic paint is treated as a waste product (73 kg CO_2e/m^3) while RWH systems made of steel drums show the highest global warming impact (827 kg CO_2e/m^3) compared to high-density polyethylene drums (79 kg CO_2e/m^3). These results suggest the viability of AC mixtures in water infrastructure such as RWH tanks to conserve resources and reduce pollution. The study concludes with takeaway benefits and constraints regarding the use of AC RWH tanks.

1. Introduction

Water-consumption is increasing due to rapid worldwide population growth (Food and Agriculture Organization of the United Nations, n.d.). Access to potable water is not always equal from person-to-person and from day-to-day, even in a developed nation such as the United States (Amit and Sasidharan, 2019). The new policies released by the United Nations under Sustainable Development Goals (SDG) aim to address this social inclusion and environmental sustainability by 2030 through goals number 6 (clean water and sanitation) and 11 (sustainable cities and communities) (United Nations, 2020). Many people who live in drought-prone areas often find themselves without the ability to use as much water as they need. Causes for this include the geographic dispersion of consumers, a lack of infrastructure to provide clean water, and the high cost of clean water for the consumers. The worldwide population most affected by the water crisis is often most vulnerable to economic or environmental hardships. Thus, the basic human needs for clean water must be satiated by means other than municipal or county water lines (Waso et al., 2018). Rainwater harvesting serves as a viable engineering solution to provide non-potable water, but storage units for such water still need to be further researched.

A rainwater harvesting (RWH) system consists of three components: 1) a catchment area, 2) a conveyance system, and 3) a storage tank. RWH tanks can be purchased ready-to-install or built on-site, and they can be built above-ground or installed below-ground (Helmreich and Horn, 2008). The effectiveness of each of these systems differs greatly when tied to rainfall in a given area and usage of water from a tank (Imteaz and Moniruzzaman, 2018). RWH tanks may be constructed from a variety of materials such as: plastic, cement, clay, soil, tile, metal, or reinforced concrete (Abdulla and Al-Shareef, 2009; Helmreich and Horn, 2008; Waso et al., 2018). This study explored the potential of using acrylic concrete as an above-ground RWH tank material.

1.1. Reinforced acrylic concrete: potential solution for RWH tanks

Acrylic concrete (AC) is a mixture of acrylic paint, sand, and Portland

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* Corresponding author.
E-mail address: azadeh.bolhari@colorado.edu (A. Bolhari).

https://doi.org/10.1016/j.rcradv.2022.200063
Received 7 October 2021; Received in revised form 11 December 2021; Accepted 28 December 2021
Available online 5 January 2022

cement. The presence of sand and cement in the mixture provides sturdiness, while the presence of acrylic paint provides some malleability and additional water-resistance (Akchurin et al., 2016). To provide flexibility in design and flexural strength, the AC can be reinforced with a mesh material (e.g., polymer, metal). The combination of these characteristics makes AC a viable candidate for RWH tanks. AC has also been used previously in other water infrastructure. This includes sparing use in developing country work, specifically in war-torn or drought-stricken areas with lack of access to clean water (Knott and Nez, 2005).

In the United States, approximately 637 million gallons of architectural paint (interior and exterior coatings) was sold in 2000, whereby an estimated 16 – 35 million gallons of paint was leftover by home consumers and retailers accepting customer returns representing 2.5% to 5% of overall sales (Greiner et al., 2004). Other estimations that include leftover paint from contractors raises the volume of leftover paint to upwards of 28 – 47 million gallons of paint (Greiner et al., 2004). Eighty percent of architectural paint is sold as water-borne, latex paint (511 million gallons) while the remaining twenty percent is sold as oil-based, acrylic paint (126 million gallons) (Greiner et al., 2004). Of those quantities, approximately 9.8 million gallons of waste latex paint can be recovered and recycled for non-paint purposes, such as incorporation into Portland cement concrete. (Greiner et al., 2004). Waste latex paint's incorporation into Portland cement concrete mixtures has shown to maintain adequate material and mechanical properties at replacement rates of upwards of 20% of the batched water (Nehdi and Sumner, 2003; Mohammed et al., 2008). Waste acrylic paints are also generated in vast quantities. Approximately 2.5 million gallons of oil-based or solvent-based paint, the most common of which is acrylic paint, can be recycled for non-paint purposes annually (Greiner et al., 2004). There are few means of redirecting waste acrylic paint away from landfills without categorizing it as a hazardous material when appropriate (Greiner et al., 2004). By diverting paint away from landfills and incorporating it into other products, such as AC, environmental impacts (e.g., global warming) can be mitigated. This diversion helps meet the United Nations SDG numbers 12 (responsible consumption and production) and 13 (climate action). Haigh (2007) studied water-based acrylic and latex paints and noted they both have similar properties to polymer admixtures commonly used in concrete manufacture but too expensive for many applications. One difference between latex and acrylic paints is that latex paints typically use water solvents whereas acrylic paints use chemical solvents, meaning that the incorporation of waste latex paint can support hydration kinetics whereas acrylic paints cannot. Such similarities in waste production loads and mechanical properties suggest the viability of AC mixtures in water infrastructure such as RWH tanks.

1.2. *Life cycle assessments of RWH systems and acrylic concrete*

Research conducted on RWH systems and AC mixtures have remained separate in the literature. The use of AC has not been examined in RWH systems or regarding its potential environmental impacts. Life cycle assessments (LCAs) have looked at different scales of RWH systems, but do not typically examine them at the scale of a single household.

LCAs of different water gathering systems often compare the following types of systems: domestic RWH, agricultural RWH, commercial RWH, municipal drinking water supplies, and centralized runoff treatment systems (Faragò et al., 2019; Ghimire and Johnston, 2017b; Ghimire et al., 2014, 2017; Morales-Pinzón et al., 2012; Vialle et al., 2015; Wang and Zimmerman, 2015). These RWH systems are large in scale, including systems for commercial buildings or entire neighborhoods as opposed to small-scale systems such as single barrels or plastic tubs. They typically require more infrastructure than systems for single households, such as pumps for distribution or underground storage tanks.

The system boundaries that are considered by RWH infrastructure LCAs vary greatly, depending upon the scale of the system. At the household scale (Faragò et al., 2019; Ghimire and Johnston, 2017a) and agricultural scale (Ghimire and Johnston, 2019; Ghimire et al., 2014; Morales-Pinzón et al., 2012), the inclusion of pumps and other infrastructure were found to increase the environmental impacts of the systems. Yet, these elements are not consistently considered across studies.

Many studies have found that smaller-scale RWH systems, such as single-household scale, are often the most cost-effective option (Gabarrell et al., 2014; Morales-Pinzón et al., 2015; Vialle et al., 2015). Sanjuan-Delmás et al. (2015) found that larger-scale drinking water tanks' materials are significant contributors to the systems' environmental impacts, which shows potential for similar trends in RWH tanks. RWH systems have been found to have fewer environmental impacts than other systems at the municipal scale when the community is densely populated (Angrill et al., 2012; Ghimire et al., 2017; Ghimire and Johnston, 2017b; Petit-Boix et al., 2018). When disaggregating the impacts to compare the performance of RWH tank materials (e.g., steel, high density polyethylene, concrete), the environmental impacts are typically reported alongside distribution infrastructure (e.g., pumps and pipes) (Ghimire and Johnston, 2017a; Morales-Pinzón et al., 2012), and acrylic concrete has not been considered as a material for tanks.

Overall, there is a gap in the literature for the LCA of common materials (i.e., plastic, steel, concrete) used in single-household-scale RWH tanks, as well as comparisons of these materials with different types of AC mixtures. In addition, the majority of studies focus on community or neighborhood-scale RWH systems instead of single-household RWH systems. Decentralized RWH systems can be adopted by families without large infrastructure needs, promoting their usage among a diverse set of communities. Thus, the novelty of this study is its focus on single-household RWH and the comparisons of AC mixtures to other common tank materials (high-density polyethylene and steel drums) on the basis of global warming as a critical environmental impact.

1.3. *Purpose of this study*

This research comprehensively analyzed the feasibility of AC mixtures to be used for RWH tanks. The flexural strength of AC mixtures made with varying dosages of acrylic paint and sand were evaluated. Two AC-RWH tanks were built in the laboratory and exposed to the atmosphere to collect rainwater for 4 months. One tank remained at the laboratory outdoors and served as the control tank. The other tank was used residentially for irrigation and served as the test tank. Water quality data was recorded for both tanks. A series of chemical and biological water quality analysis of the test and control tanks were performed. The levels of semi-volatile organic compounds (SVOCs) were measured in a batch bench experiment. Finally, an LCA was conducted to quantify the global warming impact of the different AC mixtures and other common RWH tank materials.

2. Material and methods

2.1. *Acrylic concrete (AC) mixture design and sample preparation*

Three constituent materials were used to produce various AC mixtures: Type I Portland cement, a commercially available acrylic semi-gloss paint, and commercially available play sand. The nominal mixture design was based on an earlier mix design from Bolhari (2005). Fourteen mixtures were explored, and the mixture designs are shown in Appendix A. The naming scheme for the mixture denotes the material type as well as its percent composition (by weight). For instance, C12P45S43 is the mixture used to make the test and control tanks, and it is composed of 12% Portland cement, 45% acrylic paint, and 43% sand by weight. The mixtures were selected to explore the effect of the increasing addition of Portland cement on flexural strength in AC and to explore the effect of increasing sand content on flexural strength in AC.

The reinforced-AC samples to be used for flexural strength testing were prepared by coating 2 inch by 6 inch (5.08 cm by 15.2 cm) rectangular strips of commercially available fiberglass screen (20 × 20 mesh) with a thin coat of the AC using a paint brush. The mesh was painted while lying flat on a non-absorbent surface. After an initial coat was tack-dry, the sample was flipped over to paint the other side (and enhance bonding through the mesh of the first coats on either side of the mesh). Thereafter, the mesh was repeatedly turned over until three coats had been painted onto both sides.

The thickness of each sample was taken as an average of six points. The width of each sample was averaged at three points. The lower span of a third-point loading fixture was maintained at 6 inches (15.2 cm) and was tested at a displacement-control rate of 6.5×10^{-4} in/min (1.65×10^{-3} cm/min).

2.2. *Acrylic concrete tank design*

Two full-scale AC-RWH tanks were built using reinforced-AC to serve as the control and test tanks. First, a cylindrical frame was built using metal mesh. Next, the outside and inside of the metal frame was covered with a commercially available fiberglass screen. Later, the screen was coated by thin coats of the AC using a paint brush. The AC mixtures were mixed in small batches, consisting of 750 g of Portland cement, 2718 g of commercially available acrylic semi-gloss paint, and 2628 g commercially available play sand (C12P45S43). Three successive coats were added onto each side of the fiberglass mesh, similarly to how described in Section 2.1. In the end, finished tanks were filled up with water and leaking areas were identified and coated with a screen mesh and a coat of AC. The overall dimension of the test tank was measured to be 32 inches in height and 14.48 inches in diameter. The control tank had a height of 11.71 inches and a diameter of 34.45 inches. The average thickness of both tanks was measured to be 0.5 inches (12.7 mm). The tanks provided a surface area to volume ratio of 0.1 cm^{-1}. Pictures of finished tanks are included in Appendix B.

2.3. *Water quality testing design and sample preparation*

2.3.1. *Experiment sites*

Rainwater harvesting experiments were performed from April to August of 2018 in San Angelo, a city in Central Texas (U.S. Green Building Council, n.d.) in the U.S. characterized by arid to semi-arid climates. Summer maximum temperatures average 38 °C for the highlands and 40 °C for the western deserts. The rainy season in central Texas extends from May to October, with the peak of precipitation taking place during May. The average normal annual rainfall under normal climatic conditions is 532 mm (National Climatic Data Center, 2021). Annual rainfall may vary from approximately 375 – 737 mm (Texas Water Development Board, n.d.).

The control tank was located at Angelo State University (San Angelo, TX). The test tank was implemented at full-scale in a residential area approximately 5000 ft away from the control tank. The test tank was used for household plant and garden irrigation, while the control tank was not.

2.3.2. *Field experiment for chemical analysis, coliforms, and semi-volatile organic compounds (SVOCs)*

Water quality samples were collected from the test and control tanks (made of C12P45S43) for a duration of 4 months on a weekly basis. The quality of rainwater harvested from the tanks was investigated. The chemical analysis tests determined: total alkalinity (SM2320-B), total hardness (SM2340-C), calcium hardness (SM2340-B), pH (SM4500-$H+B$), specific conductance (SM2510-B), chlorides (SM4500-Cl-B), nitrates (HACH 8171), sulfates (HACH 8051), bicarbonates (SM2320-B), calcium (SM2340-Ca-B), magnesium (SM2340-Mg-B), sodium (by calculation), potassium (by calculation), and dissolved solids (calculation). In this study, the biological analysis test was limited to verifying the presence of total coliforms (SM 9223 - Colilert). SVOC samples were collected from the test and control tanks for a duration of 4 months monthly and measured following the US Environmental Protection Agency (EPA) 8270-D method (US EPA, 2014).

2.3.3. *Bench experiment for SVOCs*

A laboratory bench experiment was set up to evaluate the potential of acrylic concrete coated mesh in generating SVOCs while in contact with the harvested rainwater. The reinforced-AC samples to be used for SVOC testing were prepared by coating rectangular strips of 0.4 cm x 3.8 cm x 1.48 cm (0.16 inch x 1.50 inch x 5.82 inch) of commercially available fiberglass screen (20 × 20 mesh) with thin coats of the AC (C12P45S43) using a paint brush. Three successive coats were added onto each side of the fiberglass mesh with the same process as described in Section 2.1. Twelve test jars were prepared by placing the rectangular specimens inside 1 L glass amber jars and then topping them off with deionized water (DIW). The jars were sealed to mimic the extreme case in the field where the tank is closed to the atmosphere. Size of the test strip in the jar was chosen based on the surface area to volume ratio of the field AC-RWH tanks, which was 0.1 cm^{-1}. Twelve control jars were prepared by filling up 1 L glass amber jars with DIW. Test and control jars were stored in a dark room with an average temperature of 19.7 °C. Triplicate samples were analyzed on day: 3, 21, 49, and 84 and analyzed for SVOCs following the EPA 8270-D method.

2.4. *Life cycle assessment (LCA) methods*

The goal of this screening LCA was to study AC-RWH tanks to understand their upfront embodied carbon. The functional unit considered was a 53.4-liter tank (the size of the test tank constructed for the water quality analysis) to collect and hold rainwater for 25 years without maintenance or replacement. Three acrylic concrete mix designs (C20P80S00, C40P60S00, C00P40S60) were considered for the functional unit.

The system boundary considered, using the EN 15,978:2011 (British Standards Institute, 2011) standard, only included life-cycle stages A1-A3 and C1-C4. Stages A4, A5 was excluded from the system boundary due to uncertainties regarding transportation distances and minimal construction activities. Similarly, stages B1-B6 were excluded from the analysis due to the tanks expecting no maintenance, repair, or refurbishment during their lifetimes. Benefits or loads beyond life (stage D) were also excluded. This system boundary is summarized in Fig. 1.

A quantity take-off was performed on each of the six mix design-tank combinations. The mass of each component is summarized in Table 1. From these quantities, the Athena life cycle inventory (LCI) database (Athena Sustainable Materials Institute, n.d.) was used to perform the LCA. This open-access database uses data representative of North America. Only the life cycle impact category of global warming was considered in this LCA.

Two scenarios were considered for the emissions of the acrylic paint. The first scenario allocated all emissions to the paint as though it were virgin material used in the fabrication of the water tanks. The second scenario considered the paint as a construction waste product and no emissions were allocated. This second scenario was considered because this study was motivated by broad instances where waste acrylic paint is available and is being diverted away from a landfill and into the acrylic concrete technology.

3. Results and discussion

3.1. *Flexural strength of reinforced AC samples*

The preparation of the various mix designs revealed significant shortfalls not well quantified by standard measures of workability. The mixtures were either overly granular or resistant to flow during any painting action onto the fiberglass meshes, or they were overly thin and

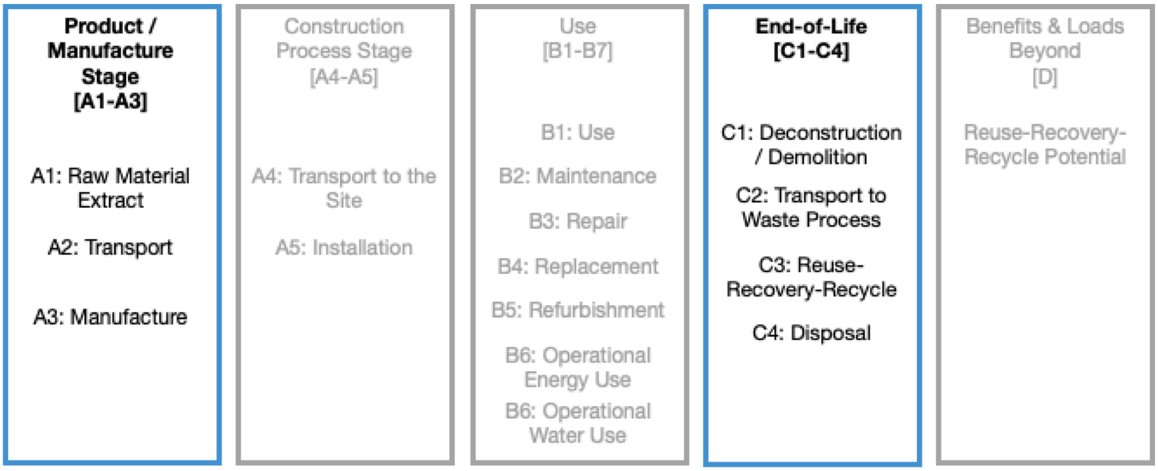

Fig. 1. Life cycle assessment system boundary for AC-RWH tanks.

Table 1
Quantity take-off (in kg) for each mix design and tank combination considered.

Tank design	Mix name	Cement	Paint	Sand	Wire mesh	Fiberglass mesh
Test	C20P80S00	0.75	2.98	0.00	0.14	0.065
Test	C40P60S00	1.41	2.11	0.00	0.14	0.065
Test	C00P40S60	0.00	1.60	2.41	0.14	0.065
Control	C20P80S00	0.91	3.63	0.00	0.37	0.079
Control	C40P60S00	1.71	2.57	0.00	0.37	0.079
Control	C00P40S60	0.00	1.95	2.92	0.37	0.079

would simply bleed through the fiberglass mesh. The observations of the mixture types are noted in Appendix C.

Of the fourteen mixtures, the mixtures C20P80S00, C40P60S00, and C00P40S60 had sufficient strength to be mechanically evaluated. These three mixtures were evaluated for their flexural strength under four-point (third-point) loading, with a lower span of 6 inches (15.24 cm). The largest flexural strength value was observed in the mixture C20P80S00 (20% Portland cement and 80% acrylic paint, by weight) at 28-days with a modulus of rupture of 266 psi. The data for these tests is shown in Table 2. The strength development is appreciable for the three tanks, meaning the curing time before transportation of AC tanks is important to ensure minimal cracking during handling and shipment.

Compression tests were not possible for the mixture types because volatilization was required for any curing and hardening. The plastic molds used to create cylindrical samples did not allow for volatilization of the AC mixture, whereas the AC tanks sufficiently volatilized in open air.

Table 2
Modulus of rupture strength values for three most mechanically viable AC mixtures: C20P80S00, C40P60S00, and C00P40S60.

Mixture name	Time of test	Average modulus of rupture (psi)	Standard deviation of modulus of rupture (psi)	Coefficient of variation of modulus of rupture
C20P80S00	7d	98.0	37.0	0.4
	14d	164.3	62.9	0.4
	28d	266.2	37.8	0.1
C40P60S00	7d	187.8	59.9	0.3
	14d	174.6	50.1	0.3
	28d	77.0	34.9	0.5
C00P40S60	7d	64.3	22.4	0.3
	14d	82.3	18.4	0.2

3.2. *Water quality data*

3.2.1. *Field experiment data*

Chemical analysis. Chemical analysis results of the water quality samples from the field experiment are depicted in Table 3. Much of the data is depicted graphically in Appendix D.

The values presented for total hardness, pH, conductivity, and dissolved solids all have ranges that overlap with the minimum and maximum value ranges presented by Abdulla & Al-Shareef (2009) for RWH tanks with roof catchment. A review from Meera & Ahammed (2006) suggests that there is wide variation in levels of calcium, magnesium, sodium, potassium, chlorides, sulfates, and nitrates in rainwater harvested with roof catchment systems. Some reasons for these variations are due to differences in roofing materials and their treatment, the air quality of the region, the orientations and slopes of roofs, and the characteristics of the precipitation (Meera and Ahammed, 2006). The roof material used for catchment of the test tank was asphalt shingles, while the roof material used for the control tank was corrugated galvanized steel panels. Mendez et al. (2011) reported the nitrate (as N) and the pH levels in polyvinyl chloride (PVC) RWH sampling inserts for roofs made of asphalt fiberglass shingles and Galvalume®. They found nitrate levels to be comparable to those found in this study. The pH levels measured for the full-scale roof testing were more acidic than those tested here (approximately 6 for asphalt fiberglass shingles and 5.6 for Galvalume®). However, this is likely attributable to the differences between asphalt versus asphalt fiberglass, and galvanized steel versus Galvalume®.

Overall, the values found in this study are comparative to those in other RWH water quality studies regarding total hardness, pH, conductivity, nitrates (as N), and dissolved solids. More information is needed to determine if the levels found for total alkalinity, calcium hardness, nitrates, chlorides, sulfates, bicarbonates, calcium, magnesium, and sodium & potassium are comparable. These chemical parameters were compared to the World Health Organization (WHO) guidelines (WHO, 2017) to show feasibility for future drinking water applications of AC-RWH tanks. Results show that all the chemical analysis parameters meet the WHO guidelines for human health justifications. Total hardness levels above 200 mg/L are not recommended due to potential scaling, however this issue has no known health effects.

Coliforms. The tanks tested positive for fecal coliforms and total coliforms (Table 3) which indicates that collected water does not meet WHO guidelines for drinking purposes (WHO, 2017). These results support those collected by Waso et al. (2018), where 69% and 62.7% of select RWH tanks in South Africa and Australia tested positive for *Escherichia coli* and *Enterococcus* spp., two fecal indicator bacteria, respectively. Meera & Ahammed (2006) also reported several studies

Table 3

Chemical analysis, coliform test, and SVOC test results of water samples from the AC-RWH tanks in the field. Bis(2-ethylhexyl) phthalate (DEHP) is the only SVOC reported because it was the only SVOC detected above the reporting limit (RL). An asterisk (*) indicates the value was determined by calculation. ND indicates no data was available or recorded.

	Days:	6		13		20		27		34		41		48		55	
Parameters	Units	Control	Test	Control	Test	Control	Test	Control	Test	Control	Test	Control	Test	Control	Test	Control	Test
Total Alkalinity	mg/L	108	352	40	28	76	156	32	72	40	96	64	ND	36	48	ND	60
Total Hardness	mg/L	124	252	48	32	76	176	24	76	36	104	64	ND	32	52	ND	64
Calcium Hardness	mg/L	96	244	32	28	68	160	20	64	32	88	56	ND	28	48	ND	60
pH Value	Std. Units	7.43	10.72	7.60	8.15	8.59	10.65	7.44	10.61	7.10	9.30	7.58	ND	7.03	8.30	ND	9.06
SP. Conductance	micromhos/cm	478	562	210	76	191	536	72	187	91	282	130	ND	77	133	ND	145
Nitrates (as N)	mg/L	4.10	4.90	5.40	2.60	7.50	2.10	1.30	1.90	2.80	2.00	3.20	ND	2.60	2.60	ND	2.20
Nitrates *	mg/L	18.04	21.56	23.76	11.44	33.00	9.24	5.72	8.36	12.32	8.80	14.08	ND	11.44	11.44	ND	9.68
Chlorides	mg/L	60	28	60	12	16	16	12	16	12	16	12	ND	12	16	ND	8
Sulfates	mg/L	59	92	23	4	28	30	5	4	6	2	9	ND	4	4	ND	11
Bicarbonates *	mg/L	131.80	429.4	48.8	34.2	92.7	190.3	39.0	87.8	48.8	117.1	78.1	ND	43.9	58.6	ND	73.2
Calcium *	mg/L	38.4	97.6	12.8	11.2	27.2	64.0	8.0	25.6	12.8	35.2	22.4	ND	11.2	19.2	ND	24.0
Magnesium *	mg/L	6.8	2.0	3.9	1.0	2.0	3.9	1.0	2.9	1.0	3.9	2.0	ND	1.0	1.0	ND	1.0
Sodium & Potassium *	mg/L	66.2	116.2	54.9	12.0	36.0	18.8	15.8	13.7	17.0	10.7	17.5	ND	15.8	14.7	ND	12.0
Dissolved Solids *	mg/L	380	787	227	86	235	332	86	159	110	193	155	ND	99	125	ND	138
Total Coliforms	org/100mL	Positive	Negative	ND	ND	ND	ND	ND	ND	Positive	Positive	ND	ND	ND	ND	ND	ND
Fecal Coliforms	org/100mL	Positive	Negative	ND	ND	ND	ND	ND	ND	Positive (E. coli)	Negative (E. coli)	ND	ND	ND	ND	ND	ND
SVOC: DEHP	mg/L	0.0105	0.0190	ND	ND	ND	ND	ND	ND	0.0107	0.00584	ND	ND	ND	ND	ND	ND
SVOC: DEHP RL	mg/L	0.00500	0.00500	ND	ND	ND	ND	ND	ND	0.00500	0.00500	ND	ND	ND	ND	ND	ND
	Days:	**62**		**69**		**76**		**83**		**90**		**97**		**104**		**111**	
Parameters	**Units**	**Control**	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**	**Control**
Total Alkalinity	mg/L	176	92	68	64	48	56	56	60	ND	92	68	ND	60	ND	52	48
Total Hardness	mg/L	48	124	56	72	40	56	52	68	ND	88	56	ND	52	ND	40	32
Calcium Hardness	mg/L	44	120	52	68	36	52	48	56	ND	52	48	ND	56	ND	36	28
pH Value	Std. Units	7.55	7.03	7.49	7.91	7.92	8.13	9.34	7.99	ND	0.48	8.47	ND	7.36	ND	7.10	6.77
SP. Conductance	micromhos/cm	196	243	154	152	101	147	103	121	ND	171	129	ND	158	ND	208	201
Nitrates (as N)	mg/L	2.40	1.70	1.70	3.20	1.20	2.20	1.60	2.40	ND	1.10	1.00	ND	1.00	ND	1.70	0.10
Nitrates *	mg/L	10.56	7.48	7.48	14.08	5.28	9.68	7.04	10.56	ND	4.84	4.40	ND	4.40	ND	7.48	0.44
Chlorides	mg/L	28	20	12	12	12	20	16	24	ND	12	12	ND	20	ND	28	28
Sulfates	mg/L	1	1	2	3	2	4	1	2	ND	2	1	ND	3	ND	3	1
Bicarbonates *	mg/L	214.7	112.2	83.0	78.1	58.6	68.3	68.3	73.2	ND	112.2	83.0	ND	73.2	ND	63.4	58.6
Calcium *	mg/L	17.6	48.0	20.8	27.2	14.4	20.8	19.2	22.4	ND	20.8	19.2	ND	22.4	ND	14.4	11.2
Magnesium *	mg/L	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.9	ND	8.8	2.0	ND	0.0	ND	1.0	1.0
Sodium & Potassium *	mg/L	81.6	1.3	16.8	10.9	14.5	18.6	15.2	16.8	ND	12.3	15.4	ND	19.5	ND	28.0	26.3
Dissolved Solids *	mg/L	355	190	143	147	108	143	128	152	ND	173	137	ND	142	ND	145	127
Total Coliforms	org/100mL	Positive	Positive	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fecal Coliforms	org/100mL	Negative (E. coli)	Positive (E. coli)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SVOC: DEHP	mg/L	<0.00500	0.00924	ND	ND	ND	ND	ND	ND	<0.00500	<0.00515	ND	ND	ND	ND	ND	ND
SVOC: DEHP RL	mg/L	0.00500	0.00500	ND	ND	ND	ND	ND	ND	0.00500	0.00515	ND	ND	ND	ND	ND	ND

that corroborated coliform levels above the standards for drinking water. Waso et al. (2018) suggest that rainwater be boiled, distilled, or filtered with pore size ≤ 1 μm if intended for intranasal use. They also suggest maintaining a free chlorine or chloramine residual of 0.5 mg/L or higher in the tanks. As such, it is recommended that the collected water should be chlorinated at least once every rainy season and preferably after the tanks are full of rainwater. Since the tanks were open to the air, the sources of microbiological contamination are animal waste present in the tanks or catchment area, such as birds and squirrels. To avoid fecal contamination, catchment areas can be cleaned prior to the rainy season (Abdulla and Al-Shareef, 2009) or the tanks can be covered.

SVOCs. Field experiment results of the SVOCs analysis are depicted in Table 3. All the data in this table is for bis(2-ethylhexyl) phthalate (DEHP) because it was the only SVOC measured within detectable levels (i.e., above the reporting limit (RL)).

DEHP is a plasticizer for polymers such as PVC, rubber, cellulose, and styrene. It is also a component of insect repellents, soaps, and detergents (US EPA, 1995). DEHP can cause acute and chronic health effects, can be carcinogenic, and can serve as an endocrine disruptor (US EPA, 1995; EWG, 2021). DEHP is often emitted from new building materials such as acrylic resins (Kim et al., 2019). It is also used as a binder in acrylic paints (Fistner, Sr., 1993). The air-water partition coefficient (K_{aw}) value for DEHP is $10^{-1.98}$ at 25 °C (Schwarzenbach et al., 2016), indicating a greater affinity to the water phase than the air phase typical of SVOCs.

The US EPA's maximum contaminant level (MCL) for DEHP is 0.006 mg/L, meaning the rainwater did not meet EPA standards in the test tank until at least day 90 and in the control tank until at least day 62.

Various phenomena could explain why the SVOC concentrations fluctuated in the test and control tanks. One reason is the different AC-water contact surface area to volume ratios between the test and control tanks. While both had an approximate ratio of 0.1 cm^{-1}, the more precise ratio for each based on the maximum amounts of water in their tanks was 0.12 cm^{-1} for the test tank and 0.08 cm^{-1} for the control tank. The water in the test tank being exposed to more AC over time would positively correlate to an increase in SVOC concentration.

Additionally, the presence of organic matter in the tanks could have caused differences in DEHP concentrations. The octanol-water partition coefficient (K_{ow}) of DEHP is $10^{4.20}$ – $10^{9.64}$ (Mitsunobu and Takahashi, 2006), indicating a greater affinity for the organic phase than the water phase. While not precisely recorded, leaves and insects were found in the tanks. The test tank had an air-water interfacial surface area of approximately 165 in^2, while the control tank had an interfacial surface area of about 932 in^2. However, more information about how much organic matter was truly present in each tank is needed to derive further conclusions. Additionally, future experiments could attempt to control these variable using screens.

Another explanation could be the tanks' exposures to sunlight. The test tank was on the southern side of the building, while the control tank was on the northern side of the building.

Additionally, the water in the test tank was being depleted over time for irrigation purposes, while the control tank water was not being removed for practical means. As such, more DEHP was present in the control tank around day 34 than the test tank because the DEHP in the test tank could have been removed with the irrigation water. This can be seen in how the test tank has a higher DEHP concentration than the control tank on Day 6, but a lower concentration on Day 34. Similarly, increases in hydraulic loading rates have also been linked to decreasing SVOC removal, specifically for DEHP in drinking water biofilters (Zhang et al., 2010). As such, the rate of DEHP removal in the test tank would be less than that of the control tank, an idea that matches the findings of this study.

It should be noted that because the test tank was being used for irrigation, the test tank and the control tank never contained the same volumes or heights of water at any given point in time. Further qualitative observations are provided at the end of Appendix D.

3.2.2. *Bench experiment data for SVOCs*

Results of the SVOC analysis from the bench-scale experiment for all three jars containing AC test strips are shown in Table 4. All the data in this table are for bis(2-ethylhexyl) phthalate (DEHP) and benzoic acid because those were the only SVOCs found within detectable levels. The three control jars each measured less than 0.00500 mg/L of DEHP and 0.0300 mg/L of benzoic acid, corresponding to each test's RLs, for all tests conducted during the experimental period. As such, the data for the control jars are not depicted in Table 4.

Benzoic acid is most commonly known as an antimicrobial food preservative (EMBL-EBI, 2020), but can be used to make various other compounds such as plasticizers and resins (CAS, 2017). Benzoic acid has been found to leach from denture-based acrylic resins (Wibbertmann et al., 2000), and as such it is possible that benzoic acid was used to make the acrylic paint used in this study. It has also been used in alkyd resins, in the paint industry, and in unsaturated polymer composite resins (Velsicol Chemical LLC, 2021). Additionally, benzoic acid was found to leach from Type I Portland Cement in small concentrations at a maximum of 0.019 mg/L over a 20-day testing period in a study from Smith et al. (2014). Benzoic acid does not have a MCL value for drinking water. The US EPA's New Chemical Exposure Limit under the Toxic Substances Control Act for benzoic acid as of March 2018 is listed as 3.2 mg/m^3, equivalent to 0.0032 mg/L, for an eight-hour time weighted average (US EPA, 2015). In addition, the US EPA lists benzoic acid as a noncarcinogen with a reference dose for oral exposure of 4 mg/kg-day under CAS NO-65–85–0 from IRIS (US EPA, 1988).

Benzoic acid was found to be present during the bench experiment, but it was not detected during the field experiment. Measured benzoic acid concentrations in the field experiment were always below the RL. Hypotheses for this finding can be found in Appendix D.

3.3. *Life cycle assessment (LCA)*

Fig. 2a visualizes the global warming impact results of the LCA. In the scenario which considers the acrylic paint as a virgin material, the paint dominates the life cycle impacts for all mix designs as noted by the large blue bars in Fig. 2a. As the quantity of paint decreases in the mix design, the environmental impact decreases. Surprisingly, cement does not have a large contribution to the overall emissions. Additionally, the wire mesh reinforcing and the sand provide minimal contributions to the total greenhouse gas emissions.

For all three mix designs shown in Fig. 2, over 99% of the environmental impacts occur in life-cycle stages A1-A3, with negligible contribution coming from the end-of-life stages (C1–C4). This distribution of environmental impact is again dominated by the large quantity of cradle-to-gate emissions from the acrylic paint.

Fig. 2b depicts the scenario when paint is considered as a waste product with no emissions allocated to it. Here, the global warming impact is significantly reduced in comparison to the scenario in Fig. 2a. The mix designs that have the least amount of cement (i.e., C00P40S60) have the lowest global warming impact. This result is expected as cement is energy and carbon intensive to manufacture in comparison to the other materials which comprise the mix design.

To reduce the global warming impact of the rainwater harvesting tanks, it is recommended to minimize the quantity of virgin paint that is used. A concrete tank of similar function is expected to have much lower global warming impacts due to the absence of paint from its mix design. Yet, in regions that are water limited, global warming impacts are only one environmental impact category that should be considered when making decisions.

The acrylic concrete tanks considered in the present study were compared to other rainwater collection tanks on the basis of global warming impact. The first was a 55-gallon plastic (high density polyethylene, HDPE) drum, a common device for household rainwater collection, and the second was a 55-gallon steel drum. The global warming impact for each of these alternatives is calculated under the

Table 4
Detected bis(2-ethylhexyl) phthalate (DEHP) and benzoic acid concentrations during the bench experimental period. No data was collected for DEHP for experimental day 3 because it was flagged for having reproducibility that exceeded the lab control limits. ND indicates no data was available or recorded.

	AC - 1				AC - 2				AC - 3			
Experiment day	DEHP Detected (mg/L)	RL (mg/L)	Benzoic acid Detected (mg/L)	RL (mg/L)	DEHP Detected (mg/L)	RL (mg/L)	Benzoic acid Detected (mg/L)	RL (mg/L)	DEHP Detected (mg/L)	RL (mg/L)	Benzoic acid Detected (mg/L)	RL (mg/L)
3	ND	ND	<0.0303	0.0303	ND	ND	<0.0300	0.0300	ND	ND	<0.0306	0.0306
21	<0.0495	0.0495	<0.297	0.297	<0.0500	0.0500	<0.300	0.300	<0.0510	0.0510	<0.306	0.306
49	0.0347	0.0253	<0.152	0.152	0.0394	0.0250	<0.150	0.150	<0.0250	0.0250	<0.150	0.150
84	0.0344	0.00505	<0.0303	0.0303	0.0279	0.00510	0.122	0.0306	0.0110	0.00500	0.0889	0.0300

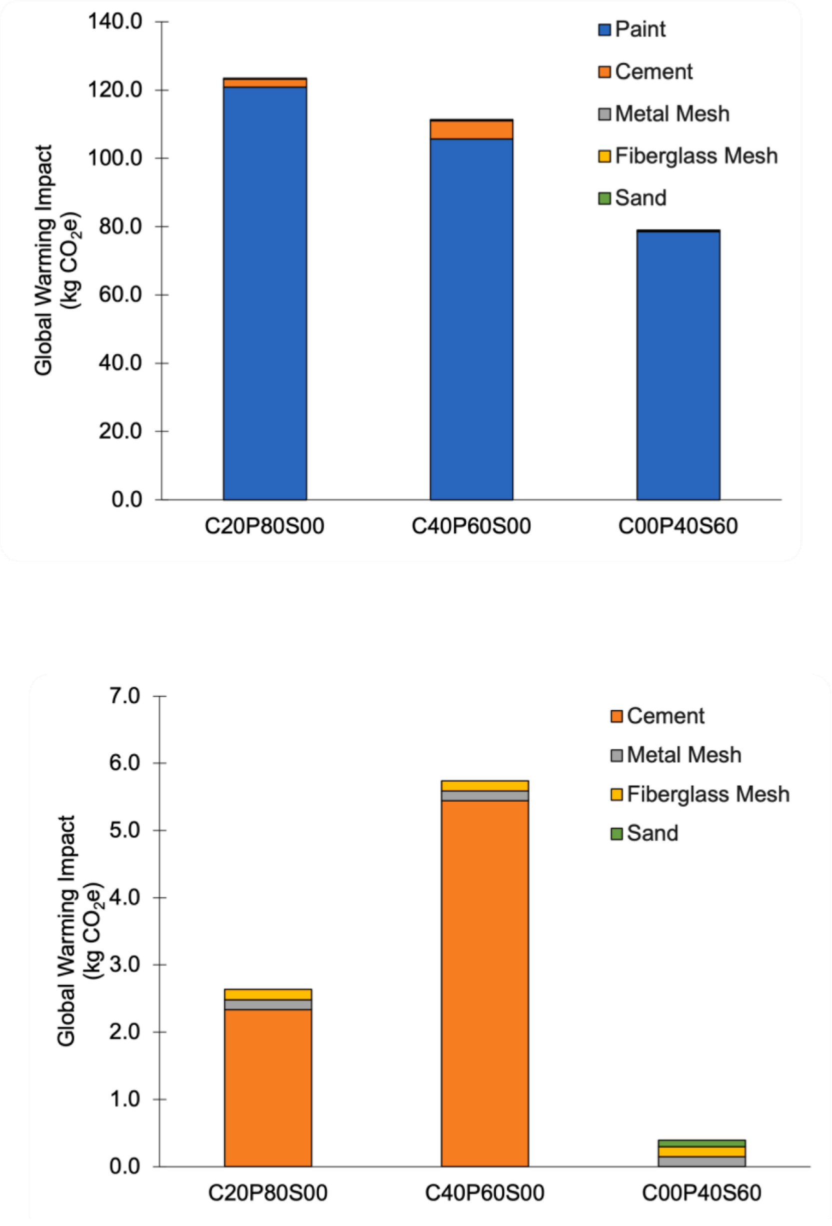

Fig. 2. (a) Global warming impact (kg CO_2e) per functional unit for different tanks and mix designs separated by contribution of each material, (b) global warming impact (kg CO_2e) per functional unit when the acrylic paint is considered as a waste product.

same system boundary. As the rainwater collection devices are different sizes and are not functionally equivalent, the resulting environmental impacts are normalized per unit volume (1 m^3) of water storage to approximate functional equivalency. The results of this normalization are presented in Fig. 3.

The C20P80S00 AC tank, when considering paint as a virgin material (first scenario), has the highest global warming impact (3425 kg CO_2e/m^3). Yet, when paint is considered as a waste product (second scenario), it has the lowest global warming impact (73 kg CO_2e/m^3). The steel tank has a higher global warming impact (827 kg CO_2e/m^3) than the HDPE

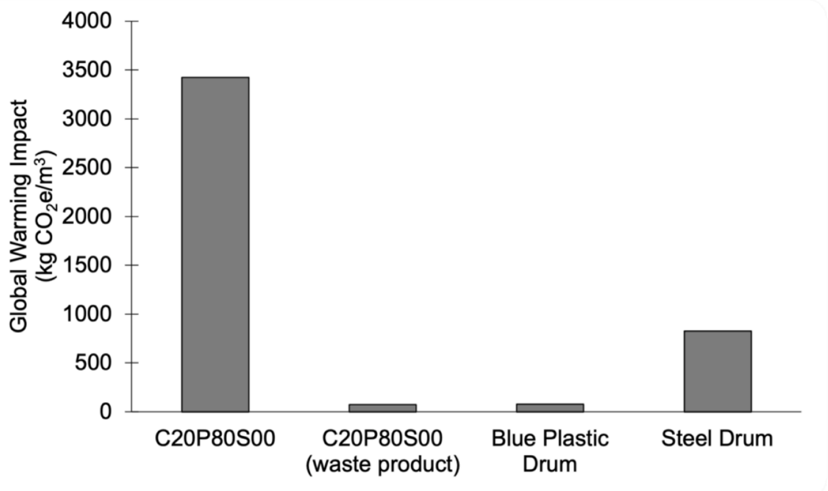

Fig. 3. Global warming impact (kg CO_2e) normalized per unit volume ($1m^3$) of the tank.

tank (79 kg CO_2e/m^3) due to steel being more carbon intensive to manufacture as compared to HDPE. There are volumetric efficiencies that the acrylic tanks (14.1 gallons) considered herein do not achieve in comparison to the larger 55-gallon tanks. Thus, it is expected that larger volume AC tanks will have lower normalized global warming impacts and be more comparable to other tanks as the volumes increase. As only a 53 l tank was the focus of this study, the ability to evaluate how a larger volume tank might compare was limited. While both Portland cement and latex paint are known to have substantial environmental impacts at scale, their GWI in the context of RWH systems is lower than that of an HDPE tank or steel drum as concluded from the life cycle assessment performed herein. This finding supports the notion that utilizing AC in a RWH system can be a sustainable through conserving resources and reducing pollution to promote the United Nations SDG12 and SDG13.

The literature that considers the life cycle impacts of RWH systems is difficult to compare across studies. As previously noted, few studies report the environmental impacts of just the storage tank, as the embodied impacts are often coupled with other infrastructure such as pumps or pipes. Yet, when the embodied environmental impacts are reported, they are distributed over the total amount of water delivered throughout a year or the lifespan of the tank. For example, Ghimire et al. (2014) found that the global warming impact of a polyethylene storage tank for a domestic RWH system was approximately 0.2 kg CO_2e/m^3 of rainwater delivered over the course of a year, depending upon the amount of rainwater collected. Likewise, Ghimire et al. (2017) also determined the global warming impact of a fiberglass commercial RWH tank to be 0.12 kg CO_2e/m^3 of rainwater supplied. Similarly, Petit-Boix et al. (2018) found that the global warming impact for a cistern and concrete pad for a densely populated municipal RWH system was 0.5 kg CO_2e/m^3 of water supplied and for a sparsely populated municipal system was 1.7 kg CO_2e/m^3 of water supplied.

The results from the present study are difficult to compare to the results of other studies, which normalize environmental impacts on the basis of 1 m^3 of water delivered as compared to 1 m^3 of water storage space within a tank. It is recommended that more transparent and nuanced results are presented in LCAs of RWH systems such that storage tanks can be accurately selected, which minimize environmental impacts such as global warming. Studies comparing other common household materials for rainwater collection, such as plastic storage tubs, can be conducted to determine if these more easily accessible materials have comparable environmental impacts to AC RWH tanks.

6. Conclusions

This experiment shows the viability of AC RWH tanks through structural, water quality, and global warming impact data. The following points show how this viability was shown and next steps to consider in future research. The study concludes with takeaway benefits and constraints regarding the use of AC RWH tanks.

This study intended to identify trends in AC mix designs and flexural strength. The mixture with 12% cement, 45% paint and 43% sand (C12P45S43) was just a "starting point" that happened to be what the one initial tank was made with. The C20P80S00 mixture was shown to be the "best" mixture, with a modulus of rupture of 266 psi. The other two viable mixtures are "weaker" and less recommendable. The C40P60S00 mixture was found to also be viable as a second-best mixture, with a modulus of rupture of 175 at 28 d followed by the C00P40S60 mixture as the third best mixture with the lowest modulus of rupture of about 80 psi.

The inorganic chemical water quality analysis was comparable to that of other studies, specifically for parameters such as: total hardness, pH, conductivity, nitrates as N, dissolved solids. More information (like studies with comparable materials used for roof, etc.) is needed to know if the values for the other parameters are comparable. That will inform if the values in this study for total alkalinity, calcium hardness, nitrates, chlorides, sulfates, bicarbonates, calcium, magnesium, and sodium & potassium are at all from AC leaching. If the values found in this study are statistically significantly different from those found in other studies, and the effects of different tank and roof materials have been considered in this analysis, then it could be concluded that the AC mixture is leaching substances that could potentially contribute to these elevated levels. Coliform levels in the AC RWH tanks were comparable to other similar studies. The collected rainwater water was not suitable for drinking in this analysis, as determining if the water was potable and how to make it potable was not a priority of this study. The leached SVOCs include DEHP and benzoic acid. DEHP was detected in both the field and bench experiments, while benzoic acid was only observed in the bench experiment. The field and test tanks traded off on which had higher DEHP concentrations, making it difficult to hypothesize within the boundaries of this study why the compound was present. While it is unknown why these concentrations in SVOCs fluctuated and why benzoic acid was not detected in the field experiment, a promising explanation is that the SVOCs sorbed to the leaves and organic matter in the field tanks. Future research should conduct further experiments to determine why these SVOCs were present in the analysis through a more specific scope and in-depth analysis. Similarly, future research should consider the leaf leachate in the RWH tanks and how that may affect the water quality in the tanks. Such considerations were not made in this study but could very well impact water quality. Future studies should evaluate the SVOC concentrations more frequently to determine how often the tank should be flushed out to prevent DEHP concentrations over the MCL and benzoic acid concentrations above EPA recommendations if the tank were to be used to collect drinking water. Rainwater harvested from any tank would require additional treatment to meet drinking water standards and regulations if so desired by the consumer. This treatment would have to consider several more parameters than SVOC concentrations. Because ambient rainwater quality differs between locations, it should be noted that different locations might have different data and regulatory standards than those considered in this manuscript. Future studies should also evaluate the water quality in AC RWH tanks when different AC thicknesses are used. A limitation of this study was that only one thickness of tank was evaluated. The question remains as to whether using thicker AC tank walls will cause different water quality measurements and SVOC concentrations to be measured in the collected water.

Through a life cycle assessment (LCA), this study determined that using virgin acrylic paint has the largest global warming impact, while using waste paint has a lower impact in comparison to steel and HDPE drums. It is recommended that LCAs showcase more nuanced results in the future to allow for more comparability between studies with different system boundaries.

Additionally, this study attempted to determine how well an AC RWH tank could supply water for domestic garden and house plant irrigation in a water-stressed region, i.e., central Texas. However, several parameters were determined after the experiment that should have been considered in the data recorded for this water balance. As such, what information was gathered and learned has been included in Appendix E for reference to others who may wish to conduct similar experiments.

Considering the feasibility of this technology, implementing RWH tank technology derived from acrylic waste paint would be a relatively easy process. The tanks can be installed at ease in new and existing buildings, and they have minimal cost for installation and maintenance. The associated labor requirements are moderate, involving water lifting and application. The tanks are low maintenance, even if additional maintenance were to be added to further improve water quality. The largest advantage of the technology is the substitution of primary paint resources by the regenerative alternative of paint waste, allowing for lower environmental impact associated with the tanks. The main constraint was the lack of suitability for drinking from the water, but that could be altered through more regular tank maintenance. Overall, AC RWH tanks show promise in water infrastructure to promote material reuse in sustainable communities, and these tanks should be further considered and researched.

CRediT authorship contribution statement

Azadeh Bolhari: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Daniel I. Castaneda:** Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jay H. Arehart:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Shelby J. Tillema:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by National Science Foundation (NSF) Award No. 1744006. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Additionally, the authors would like to thank the research assistants: Jesse Lee, Maria Ochoa, Austin Poole, Nicholas Manrique, and TJ Spies who assisted the principal investigators in this project.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2022.200063.

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