Novel Applications For Fine Glass Waste: Reuse and Recycling

A Spring 2022 Collaborative Project with Arizona State University's Project Cities & the City of Peoria

ASU Sustainable Cities Network
Arizona State University
Project Cities
Peoria Arizona

PART 1:

Project and Community Introduction

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Cover images:

Project Cities and
Shrut Kirti Chawla

ACKNOWLEDGMENTS

City of Peoria

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Jon Edwards, Vice Mayor

Bill Patena, Mayor Pro Tem

Michael Finn, City Councilmember

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On behalf of the Julie Ann Wrigley Global Futures Laboratory, the Global Institute of Sustainability and Innovation, and the College of Global Futures, we extend a heartfelt thank you to the City of Peoria for enthusiastically engaging with students and faculty throughout the semester. These projects provide valuable real-world experience for our students and we hope that their perspectives shine light on opportunities to continuously improve Peoria's future livelihood and community well-being.

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To access the original student reports, additional materials, and resources, visit:
links.asu.edu/PCPeoriaFineGlass22S

ABOUT PROJECT CITIES

The ASU Project Cities program uses an innovative, new approach to traditional university-community partnerships. Through a curated relationship over the course of an academic year, selected community partners work with Project Cities faculty and students to co-create strategies for better environmental, economic, and social balance in the places we call home. Students from multiple disciplines research difficult challenges chosen by the city and propose innovative sustainable solutions in consultation with city staff. This is a win-win partnership, which also allows students to reinforce classroom learning and practice professional skills in a real-world client-based project. Project Cities is a member of Educational Partnerships for Innovation in Communities Network (EPIC-N), a growing coalition of more than 35 educational institutions partnering with local government agencies across the United States and around the world.

ABOUT SUSTAINABLE CITIES NETWORK

Project Cities is a program of ASU's Sustainable Cities Network. This network was founded in 2008 to support communities in sharing knowledge and coordinating efforts to understand and solve sustainability problems. It is designed to foster partnerships, identify best practices, provide training and information, and connect ASU's research to front-line challenges facing local communities. Network members come from Arizona cities, towns, counties, and Native American communities, and cover a broad range of professional disciplines. Together, these members work to create a more sustainable region and state. In 2012, the network was awarded the Pacific Southwest Region's 2012 Green Government Award by the U.S. EPA for its efforts. For more information, visit *sustainablecities.asu.edu.*

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Sustainable Cities Network
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Sustainability through local action

ABOUT PEORIA

Ranked as the No. 1 place to live in Arizona by Money Magazine, the City of Peoria is currently home to over 190,000 residents. The City enjoys a reputation as a family-oriented, active community with an exceptional quality of life. Peoria entertainment and recreational amenities include attractions such as Lake Pleasant, trails, and community parks.

The City has also demonstrated a strong commitment to sustainability, as evidenced by its incorporation of LEED building design standards, a council-adopted Sustainability Action Plan, and the "Green Team" staff dedicated to managing organization-wide sustainability initiatives.

PEORIA TEAM

Project Cities Community Liaison

Sharon Roberson, Assistant to the City Manager, City Manager's Office

Spring 2022 Peoria Project Leads

Cape Powers, Water Services Director

Kristina Perez, Marketing and Communications Manager

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PEORIA ARIZONA

Peoria is the place
World class ▪ Sustainable ▪ Future Ready

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February 28, 2022

Dear Peoria community members,

On behalf of the City of Peoria, we would like to express our appreciation to all who have been involved with Arizona State University's (ASU) Project Cities program. Over the last year, our staff has had the opportunity to collaborate with faculty and students across several academic programs, benefitting from their insights, ingenuity, and diverse perspectives on a number of projects. Many of these entailed public participation, and you may have met some of these engaging students at a community event, or completed a community survey.

Project Cities is one of several partnerships we enjoy with ASU, and part of our ongoing strategy to connect with community partners to leverage our resources as we address the many challenges facing local governments. Working with students at an undergraduate, graduate and capstone project level brings a fresh perspective and resourcefulness to complex issues. This partnership has resulted in extensive research, recommendations, and deliverables that take several key initiatives to the next level. These include our efforts around increasing transit ridership, community engagement strategies, historic preservation and innovative recycling methods. Through this partnership, we have developed an understanding of the feasibility of each initiative much more quickly than we could have without their collaboration.

The results provided on each project position us to serve our community with cost-effective and innovative programs in the interest of continuous improvement. The city has already begun to incorporate the students' deliverables into next steps in advancing these projects. We look forward to continuing this work on additional projects in the coming year with such talented students and faculty.

The City of Peoria appreciates the ongoing and growing relationship with Arizona State University and the many ways in which the alliance provides mutual value.

Sincerely,

Cathy Carlat, Mayor

Jeff Tyne, City Manager

Peoria, Arizona

Proud partner of

ASU Sustainable Cities Network
Arizona State University

Project Cities

Rio Vista Recreation Center

Demographics

total population: **190,985**

median age: **35**

highly skilled and educated workforce of 85,252

11,997 veterans live in Peoria

78% of residents are homeowners

median property value: **$399,025**

33% of residents hold a Bachelor's degree or higher

median household income: **$79,700**

Schools

#3 of 131 Best School Districts for Athletes in Arizona

#5 of 40 Best School Districts in Phoenix Metro Area

#7 of 130 Best School Districts in Arizona

The Peoria Unified School District consistently receives high ratings and offers signature programs such as the Career and Technical Education programs. Deer Valley Unified School District has two highly-rated K-8 schools within the city, including an Academy of Arts.

Peoria is also home to Huntington University, a liberal arts college offering digital media education in animation, broadcasting, film, graphic design and other digital media arts.

Leading industries

Peoria, Arizona is not just a scenic suburb of Phoenix, but also a thriving economic development hub with an educated workforce and high-end residential living. There are over 4,000 employers and more than 75,000 people employed within Peoria. Leading industries include health care and social assistance, retail trade, and finance and insurance. Highest-paying industries include utilities, manufacturing and public administration. Beyond these industries, Peoria works actively to attract businesses from aerospace and defense, film and digital media, technology and innovation, hospitality and tourism, and research and development. Peoria is the place for business owners, developers and investors.

Health Care & Social Work
10,905 employees

Retail Trade
10,628 employees

Finance & Insurance
6,574 employees

History

Founded in 1886 by Midwestern settlers, Peoria is nestled in the Salt River Valley and extends North into the foothills around Lake Pleasant. Beginning as a small agricultural town, the economy received a major boost when a railroad spur line was built along Grand Avenue. The construction of the Roosevelt Dam in 1910 secured a reliable water supply, attracting more settlers to the area and business endeavors to the town center. Peoria's economy continued to have an agricultural focus for decades. Continually growing, Peoria assumed city status in 1971 with a population of 4,792. It has since grown into a city with a population over 190,000, and is renowned for its high quality of life and recreational amenities.

Sustainability

Peoria has demonstrated leadership in municipal sustainability efforts through a wide range of actions. Listed below are some of the City's sustainability accomplishments.

- Incorporation of LEED building design standards
- Appointment of a full-time city staff member who manages and coordinates sustainability initiatives
- Sustainable urban planning practices including open space planning and water management principles
- Sustain and Gain: Facebook page and brochures keep residents up to date on city sustainability efforts and ways to get involved
- Water Conservation Program: free public classes, public outreach at city events, and water rebate incentives for residents
- Council-Adopted Sustainability Action Plan: this strategic planning document, in its second iteration, ensures city departments are developing sustainability-oriented goals, tracking success metrics, and encouraging cross-communication in the preparation of Sustainability Update presentations made to the Peoria City Council on an annual basis
- Sustainable University: courses and workshops to empower residents to make small changes that make Peoria a better place to live; topics covered include residential solar, gardening, composting and recycling

Awards and recognition

- Award of Distinction for Technology Innovation, ROBO Ride Autonomous Vehicle Project, 2022 *(Arizona Forward)*
- Best Neighborhood Program for Social Revitalization/ Neighborliness, 2022 *(Neighborhoods USA)*
- No.1 City to Live, Work and Play in 2021*(Ranking Arizona)*
- Outstanding Facility Award for Paloma Community Park, 2021 *(Arizona Parks & Recreation Association*
- Best of the West Excellence in Innovation Award for Pop-up Peoria, 2021 *(Westmarc)*
- Top 15 Safest Cities in the U.S. 2017-2019 *(Wallethub)*
- 10th Best City to Raise a Family in 2018 *(Wallethub)*

Lake Pleasant

- **1886** – Peoria founded by William J. Murphy
- **1889** – First school district formed
- **1919** – Chamber of Commerce organized
- **1954** – Peoria incorporated
- **1971** – Assumed city status with a population of 4,792
- **1977** – Brewers spring training begins at Greenway Sports Complex
- **1986** – Centennial celebration
- **1994** – Peoria Sports Complex opened
- **2007** – Theater for the Performing Arts and Rio Vista Recreation Center opened
- **2012** – 20-year extension spring training agreement with San Diego Padres and Seattle Mariners
- **2017** – Selected as site of new $70M health clinic for Maricopa County Integrated Health System
- **2020**

Livability

Peoria is renowned as a great place to raise a family and start a career. A plethora of local amenities and attractions contribute to Peoria's livability. Beyond the tourist attractions of Spring Training and Lake Pleasant, the City offers many community facilities and recreational opportunities for all ages and interests such as an extensive public park system and annual community events. Peoria's dedication toward livability is also evident in the City's latest General Plan which addresses sustainable water use, housing, public services and more.

Ranked as the No. 1 place to live in Arizona and one of the best cities in the United States.

-Money Magazine and Yahoo! Finance

Peoria Sports Complex

Peoria strives to uphold these six major livability priorities in order to maintain an exceptional quality of life for its citizens:

- Arts, Cultural and Recreational Enrichment
- Economic Prosperity
- Smart Growth
- Superior Public Services
- Healthy Neighborhoods
- Integrated Transportation

Community Facilities

- Peoria Community Center
- Rio Vista Recreation Center
- Peoria Sports Complex
- Peoria Center for the Performing Arts
- 39 neighborhood parks
- 2 libraries
- 3 swimming pools
- 5 golf courses
- 9 lighted multi-purpose ball fields
- 15 tennis courts

Lake Pleasant

Urban ecology, ecotourism and recreation

Peoria is surrounded by the natural beauty of the Sonoran Desert and is home to Lake Pleasant, a 23,000-acre park and major recreational asset to the North Valley. The transient Agua Fria River and New River flow through Peoria, as do a multitude of washes and creeks. Most notable perhaps is Skunk Creek — known for the recreational trails running alongside it — which forges a connection between Peoria and Glendale. Northern Peoria is home to beautiful mountains and buttes including Sunrise Mountain, Calderwood Butte and Cholla Mountain.

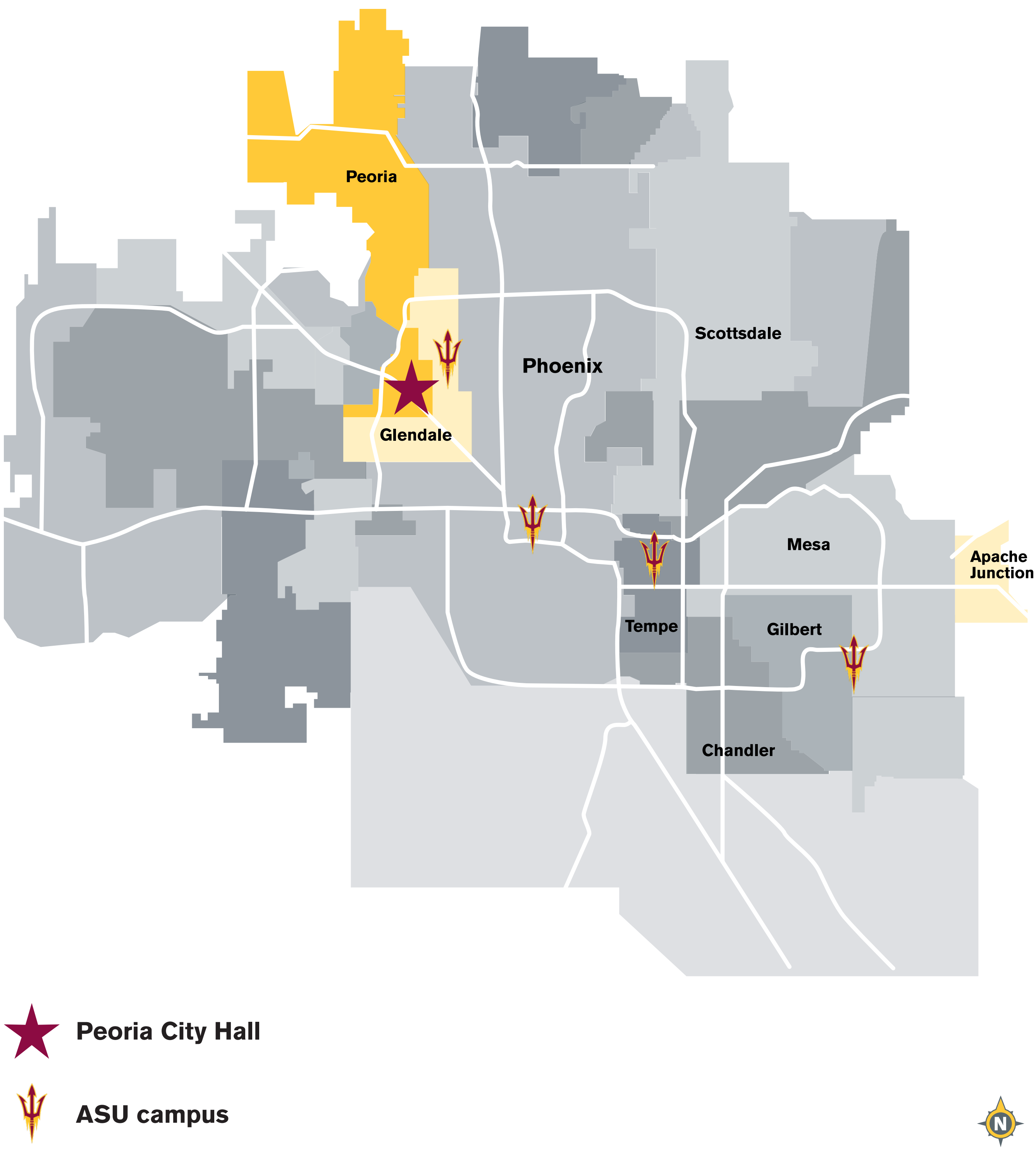
Boasting over 300 days of sunshine annually, Peoria's ecotourism opportunities are a steady industry for residents and visitors. The City features over 60 miles of trails for walking, biking and horseback riding, as well as 570 total acres of accessible park land.

Lake Pleasant Regional Park contains a full-service marina, providing opportunities for water-oriented recreation such as kayaking, water skiing and even scuba diving. Visitors can also go horseback riding, take gliding lessons, hike, camp and more.

Skunk Creek

Pleasant Harbor

MAP OF PROJECT CITIES PARTNER COMMUNITIES IN THE GREATER PHOENIX METROPOLITAN AREA



The following report summarizes and draws highlights from work and research conducted by graduate student Shrut Kirti Chawla in ERM 593 Applied Project for the Spring 2022 partnership between ASU's Project Cities and the City of Peoria.

To access the original student reports, additional materials, and resources, visit:

links.asu.edu/PCPeoriaFineGlass22S

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EXECUTIVE SUMMARY

Glass is a versatile material that offers innumerable applications in many areas. One widely used application is to store food and beverages. Besides being impervious to foreign objects, it is an inert material and provides practically infinite recycling potential. It is considered easy to recycle glass bottles and jars by crushing them to an appropriate size, then cleaning and sorting the cullet to remove contaminants. However, the process becomes more difficult when the glass breaks into smaller and smaller pieces during recovery, transportation and sorting. These pieces are called glass fines, which make their way to landfills because they are unfit for recycling due to high levels of contamination. This problem is very frequent in Material Recovery Facilities (MRFs) due to the volume of glass being sorted and processed.

Figure 1 *Small glass particles to be processed in a recycling facility*

The City of Peoria serves as a leader in adopting new methods and technologies to demonstrate its commitment to sustainability. The City aims to identify strategies to effectively manage glass fines. This project was undertaken by graduate student Shrut Kirti Chawla, as part of Senior Lecturer Al Brown's **ERM: 593 Applied Project**, to research novel applications of fine glass residue in partnership with the City of Peoria and ASU Project Cities.

This report presents research about the novel applications of glass fines, peer community survey, cost-benefit analysis, and the life cycle assessment (LCA) of the glass production process. The literature review reveals crucial information behind the application of fine glass. Many researchers have tried to incorporate glass fines in concrete in various proportions and have been successful in finding appropriate weight percentages for the highest mechanical strength. This application helps address another menacing issue, a reduction in the amount of cement used in making concrete, thereby reducing CO_2 emissions. Other applications of glass fines are involved in manufacturing foam concrete, ceramic pavers, and decorative objects like lampshades and stoneware.

Following the literature review, a cost-benefit analysis was performed to review existing recycling practices used by the City. Currently, Peoria sends its recyclables to the City of Phoenix's North Gateway Transfer Station and Waste Management Northwest Regional Landfill for further sorting and processing. As per the analysis, this contract is beneficial to Peoria as it has started receiving revenue for its recyclables beginning in October 2021.

The next step in this project involved surveying adjacent municipalities to explore how nearby cities manage glass waste. These cities tend to rely on contracting with other municipalities to dispose of or recycle the waste. Most adjacent cities do not own a MRF, and some have removed glass from their recycling programs. This step was followed by searching for vendors that recycle glass fines in Arizona. Additionally, the LCA of glass bottle production from recycled glass versus virgin glass was modeled. It was found that the recycled glass bottle production process generates almost half of the environmental impacts as compared to the virgin glass bottle production process.

Key recommendations in this project include exploring the construction sector to reuse glass fines, continuing to contract with the City of Phoenix to process recyclables, contacting GlassKing Recovery & Recycling to provide a testing sample, and reaching out to other active recyclers for premiere management of glass fines.

KEY STUDENT RECOMMENDATIONS

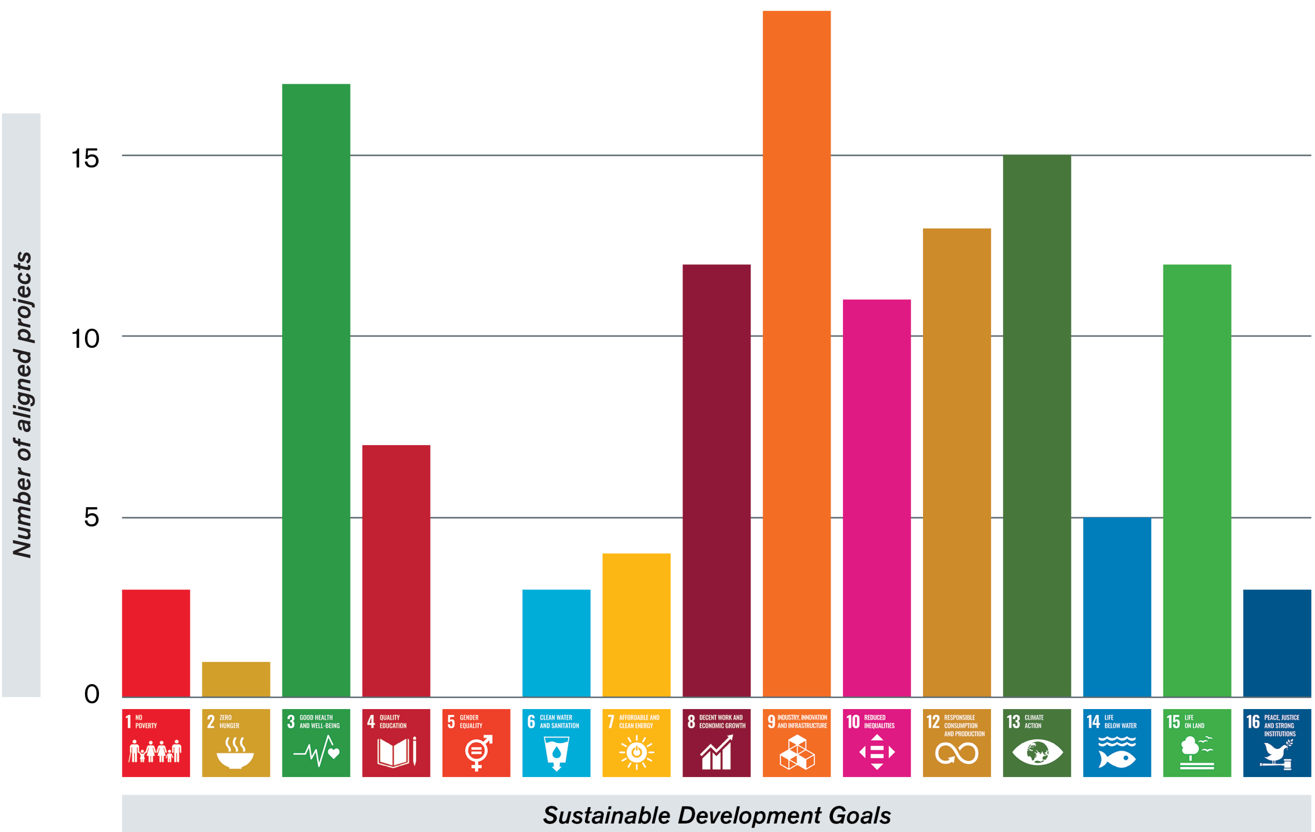
Recommendations for fine glass recycling	Read more
Consider the construction applications of glass fines, such as selling to builders for use in concrete or other products. If the City must pay a vendor for removal of the glass, municipal costs can still be reduced if the charge is less than $29 per ton.	pp.26-31, 44
Explore the applications of fine glass in ceramic and foam concrete manufacturing as another option to reduce the burden on landfills.	pp.26-31, 44
Continue with contracting with the City of Phoenix to sort recyclables, as it is a profitable alternative compared to landfilling.	pp.30-32, 44
Peoria is already ahead in the case of researching novel applications of fine glass. To maintain progress, the City can continue exploring innovative options to recycling more effectively.	pp.26-30, 44
Contact Rose King of GlassKing Recovery & Recycling to discuss potential partnerships as well as provide an initial sample for the purpose of testing the quality of the waste stream.	pp.35-36, 44
Consider contacting other recyclers in the area as well to identify further profitable business outcomes.	pp.33-36, 44

CITY OF PEORIA PROJECTS: ALIGNMENT WITH THE UNITED NATIONS' SUSTAINABLE DEVELOPMENT GOALS

As the leading international framework for sustainable decision-making, the 17 Sustainable Development Goals (SDGs) lay out a path for partnerships toward global peace and prosperity. The SDGs provide a set of goals and metrics for project impact to be measured, offering an illustration of the benefits experienced by the cities, towns, and students who participate in a Project Cities partnership. For details on the SDGs, visit **sdgs.un.org/goals.**

Every project in the PC program aligns with SDGs 11 and 17.

The figure below illustrates SDG project alignment throughout the City of Peoria's partnership with Project Cities, through the spring 2022 semester.



TOP THREE GOALS ADDRESSED IN THE FOLLOWING REPORT

This project is focused on identifying methods to recycle or reuse glass fines, a common waste product of recycling processes that tends to be landfilled. The purpose of the research is to assist Peoria's solid waste department by providing foundational information on fine glass recycling, including a cost-benefit analysis and life cycle assessment.

Goal 9: Industry, Innovation and Infrastructure

"Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation."

As recycling and waste management technologies change, it is critical to recognize new opportunities for previously discarded materials.

Goal 12: Responsible Consumption and Production

"Ensure sustainable consumption and production patterns."

Identifying opportunities to recycle more items from waste streams can help reduce demand for fresh material and spur innovative new production methods.

Goal 15: Life on Land

"Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss."

Reduced reliance on landfills can help Peoria preserve natural habitat and support local ecosystems.

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PART 2:

Fine Glass Residue Recycling and Reuse Assessment

INCREASING THE RECYCLING OF GLASS FINES BY PARTNERING WITH OTHER MUNICIPALITIES AND CONSTRUCTION ENTITIES

ERM 593:
APPLIED PROJECT

THE POLYTECHNIC SCHOOL

FACULTY:
AL BROWN

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INTRODUCTION

The City of Peoria, Arizona serves as a leader in adopting new methods to demonstrate its commitment to sustainability. It has a dedicated recycling program which further bolsters its efforts to reduce its environmental burden. The City offers co-mingled curbside recycling for residents including metals, plastics, paper, glass, and other eligible materials. Peoria sends its recyclables to the City of Phoenix's North Gateway Transfer Station for further sorting and processing. This project was undertaken to research novel applications of fine glass residue in partnership with the City of Peoria and ASU Project Cities.

Figure 1 *Aerial view of the Phoenix North Gateway Transfer Station, by Layton Construction*

Glass is an indispensable material in daily life. It is an important packaging material for food and beverages, and serves as an easy to recycle resource which helps reduce burden on landfills. However, one particularly difficult part in the recycling process occurs when glass containers break into minuscule pieces during recovery and transportation. These small pieces are called glass fines, which end up in landfills when the generator has not identified a recycling option. This is where upcycling comes into the picture. Upcycling refers to creative reuse that results in making new products from the waste material. Glass fines are one material that can be upcycled for use in various construction processes, thermal insulations, decorative pieces, and more.

Figure 2 *Sorting of recyclables at the Phoenix North Gateway Transfer Station*

For Peoria, the process of recycling starts at the Materials Recovery Facility (MRF) where glass is separated from other recyclable materials (Figure 2). This is a crucial step for the rest of the process because the waste includes contamination that increases the cost of recycling. Sorting is easier if the waste contains whole bottles or large glass pieces which are crushed into one inch-size pieces called cullet (Figure 3). However, this process results in breaking some of the glass into very small sizes that fall off the conveyor belt. This fine glass fraction contains contaminants such as ceramics, stones, plastics, and porcelain which are hard to remove, making glass fines unfit for recycling purposes. The fine glass, thus, ends up in the landfill where it takes thousands of years to break down. More research for emerging developments in reuse and upcycling applications of glass fines can yield positive results that are cost-effective and environment friendly.

Figure 3 *Glass cullet at the Phoenix North Gateway Transfer Station*

The scope of this project includes research about best practices in waste management employed in the United States, cost-benefit analysis, and to some extent the life cycle assessment (LCA) of glass. The cost-benefit analysis helps quantify the profitability of existing recycling methods while the LCA can help determine environmental impacts. The primary research questions discussed in this project include:

- What are the municipalities of Mesa, Tempe, Gilbert, and Tucson doing with fine glass?
- What vendors recycle fine glass?
- What are the costs and benefits associated with recycling fine glass residue, and the potential effect on Peoria's diversion rate?

RESEARCH METHODS

The first step in this project involves a literature review to explore existing novel applications of fine glass recycling. Australia, Europe, and the United States are investing in research revolving around potential uses of fine glass. Many researchers have presented optimum solutions to produce high quality products from glass waste. Following the literature review, subject matter experts from the cities of Tucson, Phoenix, Tempe, Mesa, and Gilbert were interviewed to further understand existing methods of fine glass waste management. Some of the selected cities own a MRF, while others have contracts with other municipalities to dispose or recycle their waste.

Next, vendors who recycle or reuse fine glass were identified. Often, vendors will clean glass cullet and sell it to container glass manufacturers. A cost-benefit analysis was then performed to evaluate if Peoria's existing recycling practices are profitable or break-even. Currently, the City of Peoria sends its recyclables to the City of Phoenix and Waste Management. These facilities sort and clean the material, then sell it to respective vendors. However, glass is not sold by Phoenix, the vendor is instead paid to remove glass waste from the MRF. Finally, the LCA of recycled glass was modeled to determine potential impacts of glass waste on the environment.

LITERATURE REVIEW

Research incorporating the use of fine glass in long-term applications is summarized in the following paragraphs.

Glass as pozzolan in concrete

The American Concrete Institute (ACI) defines pozzolan as a compound possessing no cementitious property but having an ability to convert into a cementitious compound on reaction with calcium hydroxide in the presence of moisture (ACI, n.d.). Various studies have been conducted on the use of fine glass in producing concrete and mortar by replacing cement binders to make a more sustainable construction material. Significant CO_2 emissions are generated in the cement manufacturing process, for example one ton of cement manufacturing emits close to one ton of CO_2 (Gimenez-Carbo, 2021; Malek, 2020). Waste material such as fine glass that is not recycled can be used as a cement substitute because of its pozzolanic properties. When fine glass is used in varying quantities, it exhibits different mechanical properties and strength in the resulting concrete or mortar. The usage of fine glass with different combinations of aggregates in making concrete has also been evaluated, and is further discussed in the subsequent section.

Editor's Note

Sometimes used interchangeably with the term "concrete," cement is a binding material used within concrete, mortar, stucco, and grouts. The most common type of cement is Portland cement, which is usually made from limestone.

Reusing glass fines serves two major purposes; reducing the amount of cement that further reduces CO_2 emissions generated in the cement manufacturing process; and reducing the amount of glass waste going to landfills. The following paragraphs summarize several research papers that have demonstrated beneficial applications of fine glass waste as pozzolan.

Malek et al. (2021) reported that the addition of glass sand aggregate increases the mechanical properties of mortar. They observed the greatest increase in strength in mortar containing up to 20% green glass of fine aggregate in sizes around 0-1.5 mm.

Afshinnia et al. (2016) reported "the incorporation of glass powder in concrete as a cement replacement material improved the workability of the concrete mixtures regardless of the nature of the coarse aggregate, i.e., whether crushed glass aggregate or natural mineral aggregate was used." They also reported, "when glass powder was used as an aggregate replacement material the compressive strength of concrete containing crushed glass aggregate increased." They replaced 20% of cement or aggregate with glass powder with an average particle size of 17 micrometers (μm).

Replacement of fine aggregate with 20% fine glass showed improved pozzolanic, compressive and flexural strength in the concrete as reported by Zainab et al. (2008). It reached a maximum on the 28th day of curing as fine glass is a slow pozzolan.

Ester Gimenez-Carbo et al. (2021) studied the possibility of incorporating different proportions of glass powder from waste glass (rejected material called fine cullet) produced during the glass recycling process into the manufacturing of mortar and concrete. They found that replacements up to 25% can guarantee enough strength in concrete and mortar.

Fine glass for ceramic applications

Using fine glass as a flux in ceramic pavers has been widely studied because it is easy to incorporate glass fines into the raw material. Pavers utilize clay that is abundant in the environment. Using glass waste as an aggregate helps further reduce the energy required in the firing process of paver manufacturing while also increasing the physical properties.

A study by Bohn et al. (2021) explored the incorporation of waste glass in ceramic pavers. When pavers are made using fine glass, they have properties better than their counterparts made without fine glass. They utilize lower firing temperatures, saving a lot of energy when incorporated with fine glass as a fluxing agent. Their study showed that samples containing 60% glass were produced at around 950°C, and featured the highest values of mechanical strength and lower water absorption, as well as being resistant to acid damage. The authors claimed the pavers produced at 900°C have physical properties suitable for application in industrial floors, and areas where there is light vehicular and pedestrian traffic. When fired at 950°C, pavers are suitable for use in areas with heavy vehicle traffic.

Silva et al. (2017) explored the use of fine glass in ceramic-based products, including ceramic bricks, tiles and their glazing, glass-ceramics, foam glass-ceramics, and porcelain. They found that using pulverized glass in the manufacturing of glass-ceramics not only reduces energy consumption but also offers an increase in compressive and flexural strength. Moreover, the glass cullet shows adequate performance when used as a feldspar replacement to manufacture porcelain that has low environmental impacts.

Figure 4 *Foam glass aggregate has a wide variety of construction uses*

Another study conducted by Yaghoubi et al. (2021) used 10%, 20%, and 30% portions of sand-size recycled glass (RG) as a non-chemical soil treatment. The experimental results showed up to a 113% increase in resilient modulus of clay with the addition of 30% RG. Resilient modulus is a measure of material stiffness and provides a means to analyze the stiffness of materials under different conditions, such as moisture, density, and stress level. This treatment was studied for improving the performance of expansive clay (soft-textured clay which is prone to cracking during seasonal changes) and increased pavement performance.

The incorporation of glass fines in constituent materials of brick and tiles has shown a considerable reduction in the temperature required to fire them. Phonphuak et al. (2015) obtained the same results in a study conducted to enhance the physical-mechanical properties of fired clay brick. They found the optimum waste glass content of 10% enabled the clay brick to be fired at a lower temperature of 900°C and resulted in bricks with similar strength compared to those of normal clay bricks fired at 1,000°C.

Fine glass in foam concrete

Another application of glass waste is found in producing foam concrete which possesses good thermal insulation characteristics and is a lightweight material. It is used in various construction applications such as road sub-bases, shock absorbers (due to the porous and cellular structure that absorbs stress well), and in floor screeding to level up the surface. Fine glass can be used to substitute either the fine aggregate or the cement in making foam concrete.

Gencel et al. (2022) studied physio-mechanical, durability, and insulation properties of foam concrete made using fine glass. They mentioned that "the addition of glass sand increases the compressive and flexural strengths of foam concrete. In the same fashion, the addition of glass sand has a more positive effect on the strength development of the foam concrete with a lower content of foam agent." This is attributed to the enhanced ability of concrete containing glass to withstand internal stress caused by drying shrinkage. Their best mix contained 50 kg/m^3 foaming agent, 70% glass sand and 30% expanded perlite aggregate. Thus, there is a double benefit of using glass waste in foam concrete.

A study by Khan et al. (2019) found that the direct replacement of cement with recycled glass powder (20% by mass) increased the compressive strength of foam concrete. They determined that the optimum size of fine glass should be smaller than 45 µm to prevent the alkali-silica reaction from occurring in the resulting concrete which hampers its durability. They presented data showing that 20% replacement of cement with 20% recycled glass powder achieved higher compressive strengths as compared to the sample with 40% replacement.

Figure 5 *Laying foam concrete blocks for a residential foundation*

Thus, these studies present feasible approaches for the manufacturing of sustainable construction materials as well as a solution to the problem of fine glass utilization. The studies provide examples of practical and effective use of fine glass that reduces the consumption of energy along with the burden of landfilling. The literature also describes other uses of glass fines including decorative objects, landfill cover, artisan glazes, countertops, table surfaces, etc. Different colored glass pieces look aesthetically pleasing when incorporated into a base material like resin or cement-like material, and result in sturdy countertops which are not easily scratched or burned. The glass pieces also diffuse light in unique patterns, making them ideal for use in lampshades, tiles, stoneware, etc. (Sustainability Victoria, Alex Fraser Group & Mark Douglass Designs, 2018).

Figure 6 *Recycled glass countertop (left) and lampshade (right), by Sustainability Victoria, Alex Fraser Group & Mark Douglass Designs*

REVIEW OF PHOENIX METROPOLITAN AREA GLASS RECYCLING PRACTICES

Cost-benefit analysis

The assumptions listed in Figure 7 are used to explain a brief cost-benefit analysis of glass recycling by the City of Peoria. The notes at the end of this section feature additional explanations of the evaluated parameters. The City of Peoria is charged $29 per ton to dispose of solid waste in a landfill. When it is sent to the MRF, the waste is sorted and its disposal fee goes down because some portion of it finds use, costing $19.20 per ton, and some portion is sold for revenue.

Cost-benefit analysis assumptions	
Item	***Total***
If total mixed recyclables generated per month by Peoria =	1000 tons
Other recyclables =	74% (740 tons)
Glass =	26% (260 tons)
Fine glass =	15-20% of total glass
15-20% of 260 tons =	50 tons (on average) = 5% of total recyclables
Composition of 1000 tons of recyclables =	**74% other recyclables (740 tons) + 26% glass (260 tons)**
Calculation	***Cost to Peoria***
26% glass = 21% normal glass (210 tons) + 5% fine glass (50 tons)	
21% normal glass = 210 tons = -$19.20 x 210 =	-$4032
5% fine glass = 50 tons = -$29 x 50 =	-$1450
Total cost after sorting for glass =	**-$5482 for 260 tons**
Cost per ton =	**$21.08**

Figure 7 *City of Peoria fine glass recycling cost-benefit analysis assumptions*

Before sorting:

210 tons of glass waste would cost = -$29 X 210 = **-$6,090**

After sorting:

210 tons of glass waste would cost = **-$4,032**

Net savings to Peoria = **$2,058 per month**

Summary

- If Peoria receives some revenue for fine glass, costs will be further reduced.
- Even if Peoria must pay a vendor to take its fine glass, if the amount charged is less than $29 per ton, costs are still reduced.
- If Peoria finds a vendor that will collect fine glass at no cost, the entire cost of $29 per ton is reduced to zero.

In conclusion, the City of Peoria benefits because it receives revenue from recyclables. Figure 8 shows the costs and profits for Peoria along with the blended rates and processing fee for mixed recyclables paid for the year 2021. The **blended rate** is the average sales price per ton for all materials sorted at the MRF and the **processing fee** is the cost to Peoria that it pays to the City of Phoenix. The unit price is calculated by **subtracting the processing fee from the blended rate** which is the net cost per ton charged to Peoria. From January to September 2021, the net cost per ton of recyclables was less than $29 (unit price, given in Figure 8), so it was beneficial to Peoria. From October to December 2021, the blended rate was larger than the processing cost. So, Peoria not only received the full cost of processing but also received 75% of the profit for its recyclables.

Peoria recycling costs and profits in 2021

Month	*Blended rate ($)*	[a] *Processing fee ($)*	[b] *Recyclables (tons)*	*Unit price ($)*	*Total ($)*	[c] *Cost/profit to Peoria ($)*
January	50.17	77	1578.02	-26.83	-42,338.28	42,338.28
February	50.17	77	1379.31	-26.83	-37,006.89	37,006.89
March	50.17	77	1586.03	-26.83	-42,553.18	42,553.18
April	56.25	77	1417.81	-20.75	-29,419.56	29,419.56
May	56.25	77	1091.92	-20.75	-22,657.34	22,657.34
June	56.25	77	1203.83	-20.75	-24,979.47	24,979.47
July	63.92	82.01	1286.86	-18.09	-23,279.30	23,279.30
August	63.92	82.01	1135.82	-18.09	-20,546.98	20,546.98
September	63.92	82.01	1267.36	-18.09	-22,926.54	22,926.54
October	88.48	82.01	1367.21	+6.47	+8845.85	6634.39
November	88.48	82.01	1389.65	+6.47	+8991.04	6743.28
December	88.48	82.01	1491.82	+6.47	+9652.08	7239.06

[a] Processing fee includes a landfill disposal fee ($29 per ton) and the cost of sorted glass removed from the MRF by the vendor ($19.20 per ton).

[b] Total recyclables consist of 74% other recyclables (paper, cardboard, metal, etc.) and 26% total glass waste. The 26% of total glass consists of 21% normal glass and 5% fine glass.

[c] Cost is displayed red, profit is displayed green.

Note: The scope of the analysis is limited to a comparison value of $29.00 per ton as a surrogate for the total of all costs of landfilled waste disposal to the City of Peoria. Other factors such as projected future costs are not included in the analysis.

Figure 8 *Cost and profit of all mixed recyclables sent by the City of Peoria to the City of Phoenix in 2021*

FINDINGS

What are other cities doing?

An important aspect of this project is to investigate how other cities manage fine glass waste. Subject matter experts from the cities of Mesa, Tempe, Gilbert, and Tucson, Arizona, were contacted to understand their existing practices. These cities rely on contracting with other municipalities to dispose of, or recycle their waste as they do not own a MRF.

Major questions asked of subject matter experts from the cities of Mesa, Tempe, Gilbert, and Tucson:

- What are the uses of fine glass that their city is utilizing in order to recycle/reuse the fine glass waste at their contractor's MRF?
- How many tons of glass waste does their contractor's MRF process in a month?
- How many tons/lbs/kg of fine glass waste does their contractor's MRF collect in a month?
- If they sell waste glass, what is the average price it is being sold for?
- Who are the vendors that procure glass waste from them?
- Do they have separate vendors for fine glass?
- Is there any study related to glass waste recycling/reuse that their city conducted to gain more insights on the applications?

City of Mesa

The City of Mesa does not own or operate a MRF. Mesa generates 32,249.64 tons of recyclables per month and approximately 16% (5,160 tons) of this recyclable material is glass. The City does accept glass in its curbside recycling program. Recyclables are currently delivered to United Fibers (UF) MRF in Chandler. Strategic Materials Inc. (SMI) then buys glass waste from UF. SMI pays $10 per ton for the glass if delivered to their facility, and UF incurs a cost of $6 per ton to haul it, making the net profit $4 per ton. UF does not have any data regarding final fine glass recycling applications (S. Stechnij, personal communication, March 14, 2022).

City of Tempe

Tempe's Recycling Coordinator, Dawn Ratcliffe, stated that like many cities in the Phoenix Metropolitan Area, the City of Tempe does not have its own MRF (personal communication, March 14, 2022). The City collects glass through its co-mingled program (commercial front load containers and roll-offs, and residential containers). Given an average of the last four recycling audits for Tempe, glass consists of about 16.5% of its recycling stream. For the month of February 2022, the City of Tempe collected about 760 tons of recyclables (after contamination was removed), containing approximately 125 tons of glass. Waste Management (WM) processes Tempe's recyclables at the Sky Harbor Transfer Station, and remaining waste is then transported to the Northwest Regional Landfill in Surprise, Arizona. SMI procures most of the glass generated in this area. The company Corning, located in Eloy Arizona, is also planning to accept glass from the Phoenix area and may have started recycling glass already. Ratcliffe also stated that some of Tempe's glass is used for **landfill cover.**

Editor's Note

Landfill covers are a containment method which creates a barrier between landfilled waste and the surrounding environment. Crushed glass has been used in landfill leachate collection systems and incorporated into the design of landfill cover systems.

Town of Gilbert

According to Gilbert's Sustainability Coordinator, Kelli Collins, this Town does not have a MRF and glass was removed from its recycling program in September 2021 due to various changes surrounding the recycling market (personal communication, March 24, 2022). Since glass is no longer accepted in the recycling program, it is landfilled. Gilbert has asked all residents to bag glass along with other household garbage and place it into their trash container for collection. Collins noted that Gilbert chose to focus on the most sought-after commodities and put its efforts into simplifying the recycling program. Recyclables besides glass are sent to United Fibers, which uses three different vendors with an average disposal fee is $27.66 per ton. During the 2021 calendar year, Gilbert sent approximately 20,600 tons of material to the recycling facility.

City of Tucson

Tucson's Deputy Director of Environmental Services, Pat Tapia, shared that the City only collects recyclable material, and does not operate a MRF (personal communication, March 25, 2022). Tucson's recycling program diverts about 30,000 tons of recyclables per year and 400 tons of glass per month. Currently, the City has a drop-off program for glass (Figure 9), since it was removed from the blue barrel curbside program. The glass collected is stored at the landfill and either shipped to a glass recycling company or crushed for reuse. Glass processing is contracted to Republic Services which owns and operates a MRF. Private haulers collect the glass and transport it to the MRF. Republic Services officials were contacted but did not provide additional information.

Figure 9 *Glass drop-off bin in Tucson*

Potential glass recycling vendors

GlassKing Recovery & Recycling

GlassKing Recovery & Recycling was started by Blake King in 2013 in Phoenix. The company collects glass from bars and restaurants and sends it to recyclers. They not only remove obstacles in the logistics process, but also make it easier to collect and store glass by providing containers to its customers. GlassKing will first survey a client's needs and estimate their generated waste to provide the best glass storage solutions. In a typical week, GlassKing's three trucks collect 10,000 to 20,000 pounds of glass (Yara, 2018). The company co-founder, Rose King, stated that the usage of fine glass depends on the quality of the glass along with the estimated volume per month (personal communication, April 7, 2022). Rose emphasized testing the quality to make a decision about procuring glass from a MRF.

Consolidated Resources, Inc.

Consolidated Resources, Inc. was started in 1990 to serve as a single source for industrial recycling programs (Consolidated Resources, Inc., n.d.). They collect recyclables from commercial enterprises and offer custom storage containers and pick-up services. They provide services in many surrounding areas like Chandler, Glendale, Mesa, Peoria, and Phoenix. When contacted, they were unable to provide additional details regarding their services, however there is an online contact form for interested customers at **www.consolidatedresources.com.**

Waste Connections Arizona

Waste Connections Arizona provides waste collection, transfer, disposal and recycling services. It is the third-largest waste management company in North America, and has transfer stations in Phoenix in the name of Right Away Disposal. The company operates through contracts with municipalities and offers services directly to residential, commercial, or industrial customers (Waste Connections, n.d.). Waste Connections was contacted through email for additional details, but no response was received by the close of the project.

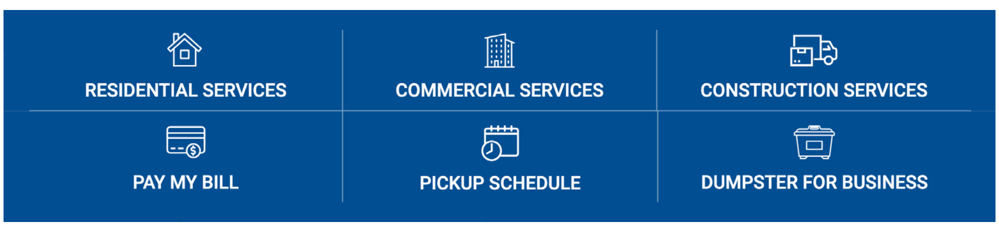

Figure 10 *Waste Connections' website features an easy to navigate menu for its service options*

Republic Services

Republic Services provides recycling and waste disposal services across the U.S. (Republic Services, n.d.). Republic has around 90 facilities that process and sell recyclables. The company invests substantially in the development of new technologies to reduce environmental impacts such as CO_2 emissions. The City of Tucson utilizes Republic Services for sorting its recyclables, as the company owns and operates its own MRF. When contacted, they were unable to provide additional details.

Life cycle assessment (LCA) comparison: Glass bottle production using recycled versus virgin glass

Goal and scope

The main objective of this LCA is to compare environmental impacts of glass bottle production between recycled glass and virgin glass. The functional unit in this study is the production of 1 kg of container glass, therefore, emissions and raw material extractions will be calculated for this level of production. Since the primary difference is between the material used, the scope of this LCA is limited to the processes as described in the following "system boundary" section. The assessment compares differences between the impacts of using fresh raw material versus glass cullet with a limited amount of fresh raw material in a standard glass production plant. The use and end-of-life process is assumed to be similar for both types of glass bottles. The study aims to show the reduced environmental impacts of glass bottle production when 50% of the batch consists of glass cullet. Using 50% glass cullet leads to reduced use of all fresh raw materials extracted from the environment, thereby reducing the overall environmental burden.

OpenLCA (version 1.11.0, 2021), an open-source software, is used for this portion of the project. Datasets for inventory and impact assessment methods were sourced from openLCA Nexus and LCA Commons web repositories. The life cycle impact assessment (LCIA) method used in this study is TRACI 2.1 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts), which was developed by the U.S. Environmental Protection Agency (EPA) and characterizes potential effects under U.S. conditions (Bare, 2012).

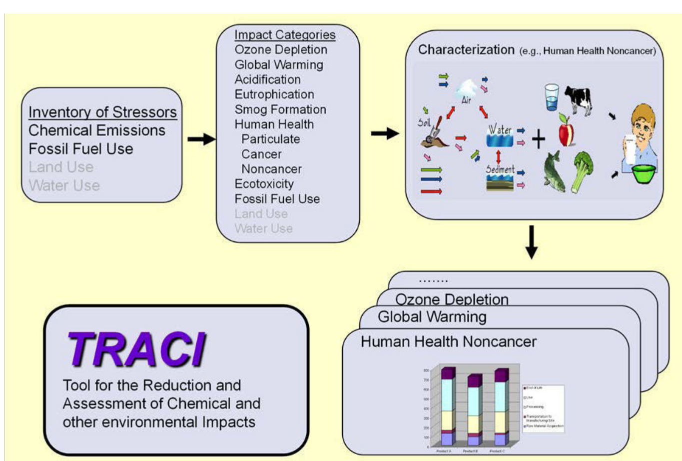

Figure 11 *TRACI 2.1 framework, from the TRACI 2.1 User's Guide by the U.S. EPA*

System boundary

The system boundary in Figure 12 shows the life cycle of glass bottle production. The green boundary captures the cradle to gate life cycle while the red boundary shows the **cradle to cradle** life cycle. Cradle to gate refers to the processes within the manufacturing facility and does not include the use phase or end of life phase. This assessment focuses on the cradle to gate boundary that includes batch preparation, melting, conditioning, forming, polishing, and final container glass production processes. **Cradle to cradle** refers to the complete life cycle with the production of products in such a way that they are recycled or reused at the end of their life and resulting in little to no waste.

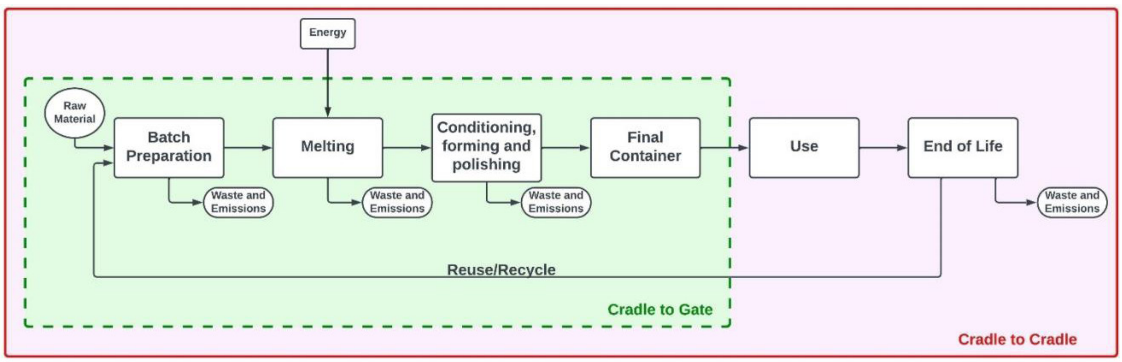

Figure 12 *Cradle to gate and cradle to cradle system boundaries in the life cycle of a glass bottle*

Life cycle inventory

Figure 13 shows the inventory for both recycled and virgin glass production processes. The difference in the inventories is the addition of glass cullet to the batch of recycled glass production. The inventory has been presented based on the commonly used input material presented in standard 'soda-lime' glass-making production processes as outlined by Glass Packaging Institute (Glass Packaging Institute, n.d.) and several research articles (Dwight & Begum, 2017; Uthayakumar, 2020). The recycled glass inventory contains 50% glass cullet which reduces the requirement for other raw materials; thereby, minimizing the burden on natural resources.

Glass production process inventory	
Recycled glass inventory	***Virgin glass inventory***
Input	
Glass cullet	-
Limestone	Limestone
Silica sand	Silica sand
Soda ash	Soda ash
Aluminum oxide (alumina)	Aluminum oxide (alumina)
Dolomite	Dolomite
Zinc oxide	Zinc oxide
Sodium sulfate	Sodium sulfate
Output	
Solid waste	Solid waste
Wastewater	Wastewater
Air emissions	Air emissions

Figure 13 *Comparison of glass production inventories between recycled glass and virgin glass production*

Life cycle impact assessment (LCIA)

The LCIA helps to interpret the significance of various environmental impacts of production processes. It includes various impact categories that are characterized as per a reference year in a particular region. Since this study has been conducted with respect to the production processes in the U.S., TRACI 2.1 is used as an LCIA method that assesses impacts at the midpoint level and relates to the assessment methods as per the U.S. EPA (Bare, 2012).

Traci 2.1 terminology

Acidification

An increase in Hydrogen ion (H^+) concentration often due to air emissions. Sulfur dioxide and nitrogen oxides from fossil fuel combustion are the largest contributors to acid rain (Bare, 2012; U.S. EPA, 2008). The model uses the term kilogram sulfur dioxide equivalent (kg SO_2 eq) for quantifying acidification.

Carcinogenic/Non-carcinogenic

Exposure to various chemicals affects the human population by causing cancers and non-cancer diseases. This model uses the term Comparative Toxicity Unit for human (CTUh) to quantify human health impacts (Bare, 2012; Hauschild, 2018).

Ecotoxicity

Terrestrial, freshwater, marine and aerial ecosystem pollution due to chemical emissions, which affects natural organisms. The model uses the term Comparative Toxicity Unit for ecosystem (CTUe) to quantify ecotoxicity (Hauschild, 2018).

Eutrophication

Increased growth of algae and weeds in lakes and streams due to excess nitrates and phosphates in aquatic ecosystems. The model uses the term kg N eq to quantify eutrophication (Bare, 2012; U.S. EPA, 2008).

Fossil fuel depletion

Impact related to the depletion of natural resources, expressed as the MJ surplus energy unit (Hauschild, 2018).

Global warming

The increase in global temperature that gives rise to changes in global climate. The primary cause of global warming is the emission of greenhouse gases due to human activities (Bare, 2012; U.S. EPA, 2008). As per the user manual, "TRACI 2.1 utilizes global warming potentials (GWPs) for the calculation of the potency of greenhouse gases relative to CO_2," hence the unit kg CO_2 eq (Bare, 2012).

Ozone depletion

The release of ozone depleting substances like chlorofluorocarbons (CFCs) leads to stratospheric ozone layer depletion. The model uses the term kg CFC-11 eq to quantify ozone depletion (Bare, 2012).

Respiratory effects

This impact arises due to the emissions of criteria pollutants, i.e., particulate matter and precursors to particulates. PM 2.5 usually arise from combustion. The model uses kg PM 2.5 eq to quantify respiratory effects (Bare, 2012).

Smog

Smog results from photochemical ozone formation and can have serious impacts on humans and vegetation, and is known to cause increased mortality (Bare, 2012). The model uses kg O_3 eq to quantify smog impacts.

Glass production process

The impact assessment is based on the key processes, inputs and flows (raw materials), and product systems that are specified by a user while modeling a LCA. The key processes involved in glass production include:

- Batch preparation
- Melting
- Final container manufacturing

Each process has specific input material that goes in and certain emissions, waste and product that come out. Every input material has emissions to air, water, land, utilization of resources like oil or gas (energy) and minerals, and waste generation resulting from their extraction processes. The datasets imported into the openLCA software provided the relevant information for each input, and were sourced from openLCA Nexus and LCA Commons web repositories. Since the functional unit here is the production of 1kg of glass, the emissions, energy, and waste are calculated per kg of the output. The software is then used to execute the following:

- Calculation of emissions, energy, and waste linked to each process and its input
- Addition of all outputs resulting from a production process
- Grouping of outputs into various impact indicators to illustrate the cumulative effect of that production process on the environment

Figure 14 shows the LCIA results of the LCA for glass bottle production when using recycled glass compared to virgin glass inputs.

LCIA results for glass production			
Indicator	***Recycled glass***	***Virgin glass***	***Unit***
Acidification	4.10E-04	9.50E-04	kg SO_2 eq
Carcinogenic	3.17E-09	7.46E-09	CTUh
Ecotoxicity	5.21E-01	1.24E+00	CTUe
Eutrophication	1.94E-04	4.60E-04	kg N eq
Fossil fuel depletion	3.52E-02	7.73E-02	MJ surplus
Global warming	4.56E-02	1.03E-01	kg CO_2 eq
Non-carcinogenic	2.34E-08	5.58E-08	CTUh
Ozone depletion	3.71E-09	8.10E-09	kg CFC-11 eq
Respiratory effects	4.74E-05	1.09E-04	kg PM2.5 eq
Smog	3.73E-03	8.25E-03	kg O3 eq

Figure 14 *LCIA results for glass production process, generated by openLCA using datasets from openLCA Nexus and LCA Commons web repositories*

In Figure 14, openLCA calculated global warming potential (GWP) for both recycled and virgin glass production processes. To do so, the software identifies the key processes and inputs (raw material) specified by the user. Then, it pulls the data for air emissions (carbon dioxide and methane) due to the combustion of fossil fuels during extraction and manufacturing of each input material from the database. The data for all inputs in a process is added and presented as GWP for that process.

Figure 15 graphs the difference between recycled and virgin glass production processes with respect to the impact category GWP. The recycled production process has 55.81% less GWP as compared to the virgin glass production process.

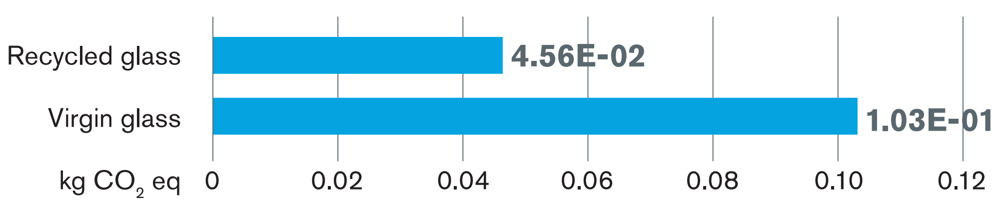

Figure 15 *Global warming potential (kg CO_2 eq) of both recycled and virgin glass production processes, as listed in Figure 14 and generated by openLCA*

OpenLCA also offers a relative comparison of impacts from two processes. For this study, each indicator's maximum result is set to 100% and the results of the other production process are displayed in relation to this result. Here, each of the impact indicators for virgin glass production process is set at 100% and the corresponding impact of recycled glass production process is presented. The relative bar chart in Figure 16 depicts the impacts of two types of glass production processes relative to each other. It is evident that the recycled glass production process has lower overall environmental impacts as compared to virgin glass production.

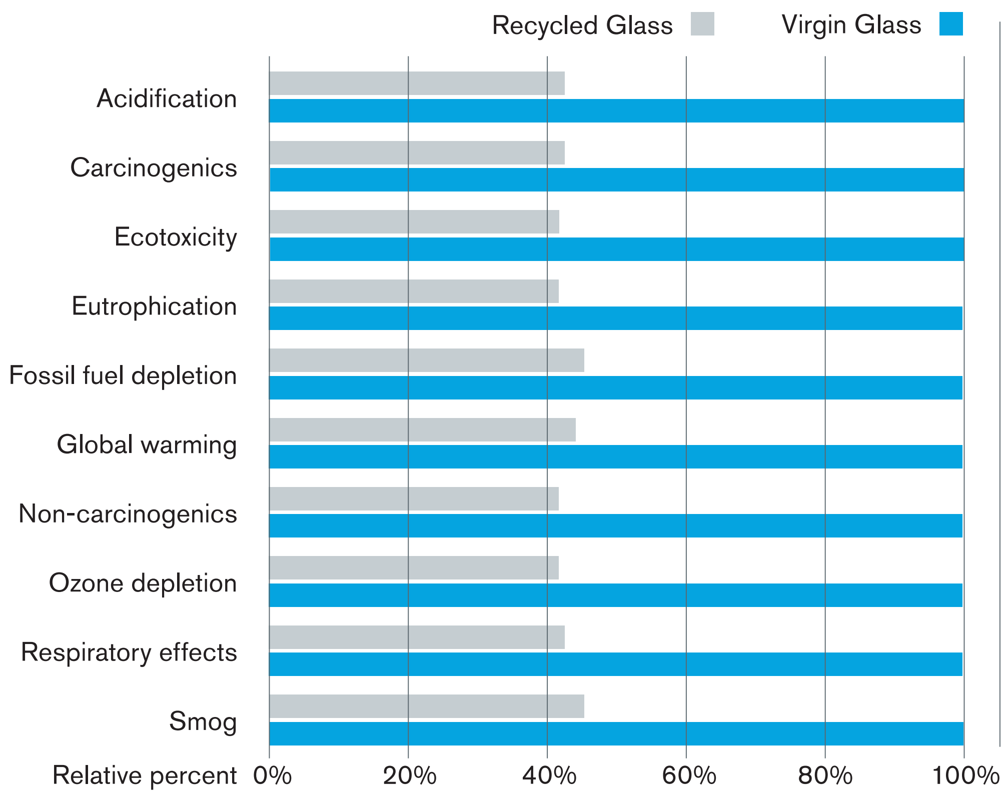

Figure 16 *Impact category comparison between recycled glass and virgin glass production, as listed in Figure 14 and generated by openLCA*

Interpretation

As seen in Figure 16, the production process for recycled glass contributes significantly less to the environmental impacts as compared to the production process for virgin glass. Ideal recycling production processes utilize around 60% of glass cullet to make the glass. This not only reduces the need for fresh raw material but also decreases the energy required for producing the glass. Recycling glass is always a good alternative as opposed to landfilling the glass waste or extracting raw materials from the earth to produce virgin glass.

Assumptions and limitations

- The transportation of raw material for batch production has not been taken into consideration in this report. The comparison was done only on the basis of the difference in raw material in both the processes and transportation has been assumed to be similar for both production processes.
- The virgin glass production system is assumed to contain zero glass cullet and all fresh raw material.
- The material that went in the batch production and the resultant glass that came out of the furnace was assumed to be equal, thus, zero loss of mass was assumed in this study.
- This study only accounts for the production of container (bottle) glass and not any other type of glass.

RECOMMENDATIONS

- As seen in the literature review, fine glass has been successfully used in various construction purposes. So, the City of Peoria can consider exploring this application in the future. If the fine glass is sold, it is a profit for the City. On the other hand, if the City must pay some amount to the vendor that is less than $29 per ton, then the City's costs are reduced as compared to the alternative of landfilling.
- Consider the applications of fine glass in ceramic and foam concrete manufacturing as viable options to reduce the burden on landfills.
- Continue contracting with the City of Phoenix to sort recyclables as it is a profitable alternative compared to landfilling.
- All the cities that were surveyed use the MRF services of big waste management companies. None of these cities are concerned with the applications of fine glass nor have any related data. So, Peoria is already ahead in this case as it is exploring the novel applications of fine glass. It is recommended to continue exploring innovative options for effective recycling.
- Contact Rose King of GlassKing Recovery & Recycling to provide a sample for the purpose of testing the quality of the waste stream.
- There are other potential recycling vendors who are highly active in Arizona. Consider reaching out to other recyclers to search for profitable business outcomes.

CONCLUSION

The City of Peoria has shown its commitment to sustainability in many ways. Addressing glass fines as part of its solid waste management is yet another facet of the City's dedication to its residents and surrounding environment. By identifying alternative uses for glass cullet, this project intends to assist Peoria leadership with finding feasible ways to reduce the amount of glass ending up in landfills without incurring excess costs.

Potential fine glass uses were first identified through a literature review, which revealed multiple novel applications for the product, such as construction materials or uniquely designed home goods. This foundational knowledge allowed for meaningful interviews with various municipal representatives from cities across the Phoenix Metropolitan Area. Through these interviews, additional glass fine uses were identified as well as different methods for glass collection. Potential vendors for the City of Peoria to consider partnering with to assist with glass recycling were also identified and their different services summarized. Finally, a cost-benefit analysis and life cycle assessment were conducted to illustrate the potential financial value of reusing glass fines, as well as the associated reduction in harmful effects.

The recommendations outlined in this report can serve as a broad starting point for the City of Peoria to further investigate its glass recycling options. As Peoria continues to grow, so will its demand for landfill space and effective waste management. This project identifies multiple ways to tackle one specific portion of the waste stream, in turn reducing the city's burden on landfills and its environmental impact.

Figure 17 *Graduate student Shrut Kirti Chawla and ERM 593 Senior Lecturer Al Brown visit the Phoenix MRF*

REFERENCES

Afshinnia, K., & Rangaraju, P. R. (2016, May 12). Impact of combined use of ground glass powder and crushed glass aggregate on selected properties of Portland Cement Concrete. *Construction and Building Materials, 117,* 263-272. **https://doi.org/10.1016/j.conbuildmat.2016.04.072**

American Concrete Institute. (n.d.). *Technical questions.* Retrieved April 2, 2022, from **https://www.concrete.org/tools/frequentlyaskedquestions.aspx?faqid=688**

Bare, J. (2012, June 18). *User's manual - pré sustainability.* Environmental Protection Agency. Retrieved April 2, 2022, from **https://pre-sustainability.com/legacy/download/TRACI_2_1_User_Manual.pdf**

Bohn, B. P., Mühlen, C. V., Pedrotti, M. F., & Zimmer, A. (2021, February 9). A novel method to produce a ceramic paver recycling waste glass. *Cleaner Engineering and Technology, 2.* **https://doi.org/10.1016/j.clet.2021.100043**

Consolidated Resources Inc. (n.d.). *About Cri: Phoenix Industrial Scrap Metal Recycling.* Retrieved March 28, 2022, from **https://consolidatedresources.com/about/**

Dwight, D. W., & Begum, S. (2017, August 28). 1.10 glass fiber reinforcements. *Comprehensive Composite Materials II, 1,* 243-268. **https://doi.org/10.1016/B978-0-12-803581-8.03812-1**

Gencel, O., Bayraktar, O. Y., Kaplan, G., Arslan, O., Nodehi, M., Benli, A., Gholampour, A., & Ozbakkaloglu, T. (2022, January 5). Lightweight foam concrete containing expanded perlite and glass sand: Physico-mechanical, durability, and insulation properties. *Construction and Building Materials, 320.* **https://doi.org/10.1016/j.conbuildmat.2021.126187**

Gimenez-Carbo, E., Soriano, L., Roig-Flores, M., & Serna, P. (2021, May 31). Characterization of glass powder from glass recycling process waste and preliminary testing. *Materials (Basel, Switzerland), 14*(11). **https://dx.doi.org/10.3390%2Fma14112971**

Glass Packaging Institute. (n.d.). *Glass composition.* Retrieved April 7, 2022, from **https://www.gpi.org/glass-composition**

Glass Packaging Institute. (2010). *Complete Life Cycle Assessment of North American Container Glass.* Retrieved April 6, 2022, from **https://assets.noviams.com/novi-file-uploads/gpi/pdfs-and-documents/Learn_About_Glass/LCA_-_GPI2010_-_compressed.pdf**

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life cycle assessment: Theory and practice.* Springer International Publishing.

Ismail, Z. Z., & AL-Hashmi, E. A. (2008, October 10). Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management, 29*(2), 655-659. **https://doi.org/10.1016/j.wasman.2008.08.012**

Khan, Q. S., Sheikh, M. N., McCarthy, T. J., Robati, M., & Allen, M. (2019, January 3). Experimental investigation on foam concrete without and with recycled glass powder: A sustainable solution for future construction. *Construction and Building Materials, 201,* 369-379. **https://doi.org/10.1016/j.conbuildmat.2018.12.178**

Małek, M., Łasica, W., Jackowski, M., & Kadela, M. (2020, July 17). Effect of waste glass addition as a replacement for fine aggregate on properties of mortar. *Materials (Basel, Switzerland), 13*(14). **https://dx.doi.org/10.3390%2Fma13143189**

Minnesota Department of Transportation. (2022). *Road research: Resilient Modulus Testing.* Retrieved March 16, 2022, from **http://www.dot.state.mn.us/materials/mr/#:~:text=Resilient%20Modulus%20(Mr)%20is%20a,moisture%2C%20density%20and%20stress%20level.**

Open LCA. (2021). *OpenLCA (Version 1.11.0).* Retrieved March 5, 2022, from **http://www.openlca.org/**

Phonphuak, N., Kanyakam, S., & Chindaprasirt, P. (2015, October 27). Utilization of waste glass to enhance physical–mechanical properties of fired Clay Brick. *Journal of Cleaner Production, 112,* 3057-3062. **https://doi.org/10.1016/j.jclepro.2015.10.084**

Republic Services. (n.d.). *Residential recycling services.* Retrieved March 28, 2022, from **https://www.republicservices.com/residents/recycling**

Siddika, A., Hajimohammadi, A., Ferdous, W., & Sahajwalla, V. (2021, November 14). Roles of waste glass and the effect of process parameters on the properties of sustainable cement and geopolymer concrete-a state-of-the-art review. *Polymers, 13(*22). **https://dx.doi.org/10.3390%2Fpolym13223935**

Silva, R. V., Brito, J. de, Lye, C. Q., & Dhir, R. K. (2017, August 25). The role of Glass Waste in the production of ceramic-based products and other applications: A Review. *Journal of Cleaner Production, 167,* 346-364. **https://doi.org/10.1016/j.jclepro.2017.08.185**

Sustainability Victoria, Alex Fraser Group and Mark Douglass Designs. (2018, May 26). *Using recycled glass fines in construction and product design.* Retrieved January 23, 2022, from **https://www.sustainability.vic.gov.au/news/news-articles/using-recycled-glass-fines-in-construction-and-product-design**

U.S. Environmental Protection Agency. (2021). *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI).* Retrieved April 15, 2022, from **https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci**

U.S. Environmental Protection Agency. (2008). *U.S. Climate Policy and Actions.* Retrieved April 2, 2022, from **http://epa.gov/climatechange/policy/index.html.**

Uthayakumar, A. (2020, March 1). *Life cycle assessment of glass bottle.* ResearchGate. **https://www.researchgate.net/publication/344552941_Life_Cycle_Assessment_of_Glass_bottle**

Waste Connections. (n.d.). *Waste diversion and beneficial reuse.* Retrieved March 28, 2022, from **https://www.wasteconnections.com/services/landfill-and-transfer-stations/waste-diversion-and-beneficial-reuse/#3300**

Waste Connections of Arizona. (n.d.). *Disposal/Recycle Guide.* Retrieved March 31, 2022, from **https://www.wasteconnections.com/arizona/disposalrecycle-guide/#**

Yaghoubi, E., Yaghoubi, M., Guerrieri, M., & Sudarsanan, N. (2021, August 3). Improving expansive clay subgrades using recycled glass: Resilient modulus characteristics and Pavement Performance. *Construction and Building Materials, 302*. **https://doi.org/10.1016/j.conbuildmat.2021.124384**

Yara, G. (2018, June 21). Glassking founder helps solve recycling problem for Valley's hottest bars and nightclubs. *The Arizona Republic.* **https://www.azcentral.com/story/news/local/phoenix/2018/06/21/glassking-takes-recycling-challenge-phoenix-area-bars-clubs/526362002/**

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