Science of the Total Environment 651 (2019) 1011–1019

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Roofing material and irrigation frequency influence microbial risk from consuming homegrown lettuce irrigated with harvested rainwater

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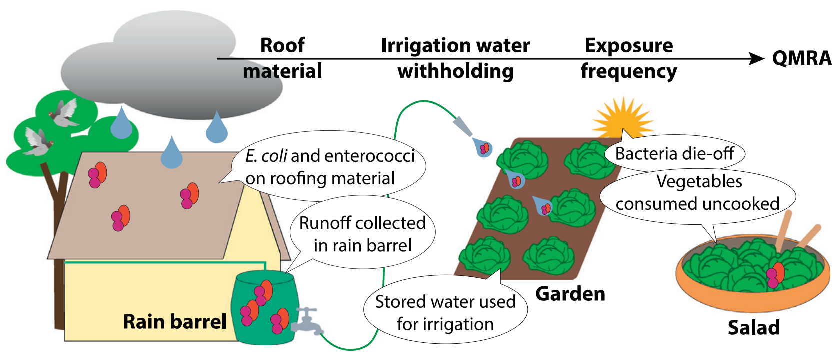
HIGHLIGHTS

- Bacterial loads were highest from wood shake and asphalt shingle roofs.
- Illness probability influenced by roof type and irrigation and exposure frequency
- *Enterococcus* more frequently detected than *E. coli* in roof harvested rainwater

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 August 2018
Received in revised form 20 September 2018
Accepted 20 September 2018
Available online 21 September 2018

Editor: Frederic Coulon

Keywords:
Microbial risk assessment
Rooftop harvested rainwater
Irrigation of produce
Roofing material
Water quality

ABSTRACT

Rooftop harvested rainwater has become an alternative, potable, and non-potable water source used around the world. In the United States, rooftop harvested rainwater is most commonly used for irrigation. Rooftop harvested rainwater may contain contaminants from bird or animal feces that may present a risk to water users. Different roofing materials may influence the survival of fecal bacteria on the rooftop prior to runoff during rainfall. In this study, three pathogen groups (*E. coli*, enterococci and *Salmonella enterica*) in rooftop runoff from three, replicated roof types (asphalt shingle, synthetic slate, and wood shake) were quantified in multiple rain events. Matched roofs were selected from locations with differing amounts of tree cover. Enterococci were the most frequently detected bacteria from all roof types. Wood shake and asphalt shingle roofing materials had the poorest microbial water quality. Rainwater runoff from two of the six buildings failed to meet United States Food and Drug Administration microbial standards for irrigation water. A quantitative microbial risk assessment indicated that the annual probability of illness from consuming lettuce irrigated with rooftop harvested rainwater varied by roofing material, irrigation water withholding period, and exposure frequency. Consuming lettuce immediately after irrigation with rooftop rainwater presented the highest human health risk based on the probability of illness from *E. coli* and enterococci exposure. Withholding irrigation by 1 day prior to harvest decreased the annual probability of illness from *E. coli* by 2 log, but had a minimal effect on the risk from enterococci.

1. Introduction

Increasing extreme weather phenomena and water scarcity have presented challenges to water security in recent years. Harvesting rainwater from rooftops represents an effective and sustainable source of

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https://doi.org/10.1016/j.scitotenv.2018.09.277
0048-9697/© 2018 Published by Elsevier B.V.

water to augment supplies in arid regions (Abu-Zreig et al., 2013). This harvested rainwater can be stored to supplement household or outdoor irrigation needs. In the United States, most individuals who harvest rainwater use it as an inexpensive alternative water source for irrigation (Thomas et al., 2014). Rainwater harvesting and use in the United States is regulated at the state level, although many states either have no guidance or limit the amount of rainwater that can be collected due to prior appropriation of water rights (Ennenbach et al., 2018). Although harvested rooftop rainwater is an economically and environmentally appealing source for irrigation purposes, it is important to be aware of the risks associated with using harvested rooftop rainwater and the various factors that might contribute to an increased risk.

Contaminants identified in roof harvested rainwater tanks include pathogens (Ahmed et al., 2008; Hamilton et al., 2006), total and fecal indicator bacteria such as *Escherichia coli* (*E. coli*) and enterococci (Hamilton et al., 2006; Lee et al., 2012), metals, total suspended solids, and turbidity (Lee et al., 2012; Mendez et al., 2011). It has been reported that these contaminant concentrations can vary depending on the type of roofing material from which the water is collected (Mendez et al., 2011). A recent study reported that *E. coli* CFU $(100\ \text{mL})^{-1}$ in rain barrels collecting rooftop runoff varied from values below the lower limit of detection to an average of 2 on galvanized steel, concrete tile, clay tile and wood shingle roofs, while enterococci was below the lower limit of detection in the rain barrels. In contrast, the first flush runoff values for *E. coli* were significantly higher, up to 14 CFU $(100\ \text{mL})^{-1}$ (Lee et al., 2012). Others have reported that fecal and total coliforms in runoff from asphalt shingles were greater than those from metal or concrete tile roofs (Mendez et al., 2011).

Potential contaminants in water should be considered when selecting how the harvested rainwater is used as certain water uses can present a greater health risk than others. For example, in a study assessing the health risk of norovirus and adenovirus from harvested urban stormwater, researchers found food crop irrigation with stormwater to present the greatest risk to human health when compared to toilet flushing and showering (Lim et al., 2015). Estimated health risk from pathogens in water, arises from the exposure routes evaluated, the frequency of exposure to the water contaminants and the concentration of contaminants present in the water. One method used to estimate the likelihood of illness from exposure to waterborne pathogens is with quantitative microbial risk assessment (QMRA) models. Previously, QMRA models have been used to evaluate the risk from using reclaimed wastewater for irrigation of various produce such as cucumbers (Shuval et al., 1997), lettuce (Petterson et al., 2001), broccoli and cabbage (Hamilton et al., 2006). To date there are no reports of the influence of roofing material type on the risk from using roof harvested rainwater for food crop irrigation.

For this study, a QMRA was used to evaluate the risk to gardeners consuming lettuce irrigated with rooftop harvested rainwater from a variety of roofing materials. A Bayesian approach was used to include the uncertainty associated with bacteria decay rates, human body mass, volume of lettuce consumed, dose-response relationships, and pathogen concentrations. The effect of uncertainty in parameter estimates on the annual probability of illness from lettuce consumption was determined by a sensitivity analysis. The results of this study provide states, governments, urban farmers and development organizations with a decision support framework to help support guidance development in the safe use of rooftop harvested rainwater for irrigation of produce.

2. Materials and methods

2.1. Sampling sites

Six buildings on the University of Utah campus were selected which had either asphalt shingle, wood shake, or synthetic slate roofs. The six sample sites were separated into two different areas of the campus: upper campus (east) and lower campus (west). These different areas on campus have different tree canopy densities. Each building with one roofing type on upper campus had a matched building pair with the same material on lower campus. The two areas were approximately 2000 m apart and differed in elevation by 100 m. The selected buildings and their characteristics are shown in Table 1.

The tree canopy density was used to approximate the presence of birds and potentially bird feces on the roofs. The tree canopy density was based on vegetation data and calculations performed in ArcMap 10.4.1 (Environmental Systems Research Institute, Redlands, California, USA). This vegetation data is a comprehensive map of land coverage of Salt Lake City including data on the locations of coniferous and deciduous trees. A buffer with a one-kilometer radius was created around each of the buildings sampled (on both upper and lower campus), and the tree maps were clipped to the respective buffers. The areal extent in m^2 of coniferous trees and deciduous trees within a one-kilometer radius of each building were estimated using the ArcMap calculate geometry function. The tree canopy is denser on the lower campus with approximately 35% greater areal extent of trees (m^2). A Tukey test was used to determine the significance between upper campus and lower campus tree densities at the 0.05 significance level. Additionally, more birds are observable on the lower campus (data not shown). It was expected that buildings on the lower campus would have more bird feces because of the higher tree canopy density and more observable birds on lower campus.

2.2. Sample collection methods

During or immediately after rainstorms, rooftop rainwater runoff samples were collected from the downspouts of selected buildings in duplicate autoclaved, 1-liter Nalgene bottles. One upper campus building with synthetic slate does not have a downspout, so water was collected during rainstorms by holding a sterile Nalgene bottle under a place of continuous flow from the roof. On average, samples were collected within 6 h after rainstorms began. After collection, samples were then taken back to the laboratory and stored in a refrigerator at 4 °C until processing. Processing of the samples for *E. coli* and enterococci culture-based counts occurred within 24 h of collection. A total

Table 1
Sampling site characteristics.

Roof material	Location	Total roof area (m^2)	Roof installation year	Elevation (m above sea level)	Areal extent of trees within 1 km radius (m^2)[#]	
					Coniferous	Deciduous
Asphalt shingle	Lower campus	130	2003	1410	88,124[a,b]	932,252[c]
Asphalt shingle	Upper campus	2800	2012	1490	35,044[b,a]	550,344[d]
Wood shake	Lower campus	1130	1997	1430	81,393[a,b]	842,744[c]
Wood shake	Upper campus	190	2000	1510	24,127[b,a]	618,142[d]
Synthetic slate	Lower campus	1050	2006	1420	82,627[a,b]	864,289[c]
Synthetic slate	Upper campus	500	2001	1500	29,934[b,a]	622,849[d]

[#] Means with the same letter are not significantly different (Tukey test) at a $P = 0.05$ level.