Journal of Agromedicine

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/wagr20

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To cite this article: Caitlin A. Ceryes, Elizabeth Nussbaumer, Emma E. Moynihan, E. R. H. Moore, David C. Love, Jacqueline Agnew, Roni Neff & Jillian Fry (2025) Health and Safety in U.S. Chesapeake Bay Oyster Aquaculture: A Qualitative Study, Journal of Agromedicine, 30:2, 360-375, DOI: 10.1080/1059924X.2025.2462321

To link to this article: https://doi.org/10.1080/1059924X.2025.2462321

Published online: 24 Feb 2025.

JOURNAL OF AGROMEDICINE
2025, VOL. 30, NO. 2, 360–375
https://doi.org/10.1080/1059924X.2025.2462321

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Health and Safety in U.S. Chesapeake Bay Oyster Aquaculture: A Qualitative Study

Caitlin A. Ceryes [a], Elizabeth Nussbaumer [b,c], Emma E. Moynihan [c*], E. R. H. Moore [c*], David C. Love [b,c], Jacqueline Agnew [c], Roni Neff [b,c], and Jillian Fry [a]

[a]Department of Health Sciences, Towson University, Towson, MD, USA; [b]Center for a Livable Future, Johns Hopkins University, Baltimore, MD, USA; [c]Department of Environmental Health and Engineering, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA

ABSTRACT

Objectives: Aquaculture seafood production exists on every inhabited continent. Small-scale, bivalve shellfish farming is a growing industry on the East Coast of the United States. Aquaculture workers in the US experience high injury and illness rates relative to the average worker, and many small-scale aquaculture operations are exempted from national injury and illness reporting requirements. Given current evidence of occupational safety and health (OSH) risks, planned industry expansion, and limited systematic OSH data collection from small aquaculture farms, it is critical to understand challenges and opportunities to promote worker safety and health on these operations.
Methods: We conducted in-depth interviews with nine oyster producers in Maryland ($n = 8$) and Virginia ($n = 1$) to document their perspectives on occupational safety and health (OSH) issues.
Results: Respondents reported various hazards and safety interventions spanning the hierarchy of controls. Many desired better access to safety training and interventions.
Conclusions: This study contributes to global efforts to improve safety and health in the fast-growing aquaculture sector. Like other developing aquaculture industries, Chesapeake Bay shellfish aquaculture producers face significant OSH challenges, with limited safety resources and guidance. Governmental industry development support should include funding for robust and industry-inclusive OSH surveillance and interventions, concentrating on the most effective hazard control measures, including elimination, substitution, and engineering controls.

KEYWORDS
Aquaculture; hierarchy of controls; injury prevention; occupational safety and health; shellfish; worker health

Introduction

Aquaculture, i.e., farming aquatic organisms including fish, mollusks, and aquatic plants,[1] represents a fast-growing global food production sector. The United States industry, which is relatively small when compared to other nations, accounts for 7% of domestic seafood production by volume and 24% by value, occurring in freshwater and marine settings.[2] Bivalve mollusk production (including oysters, clams, and mussels) comprises 80% of marine aquaculture production by value, and occurs primarily on the U.S. Pacific, Atlantic, and Gulf coasts.[2]

Shellfish aquaculture occupational safety and health (OSH)

Shellfish aquaculture production combines occupational hazards of fisheries and agriculture, and gaps exist regarding hazard characterization and mitigation strategies.[3,4] A growing literature base examines risks facing shellfish aquaculture workers in various contexts. Recognized bivalve aquaculture hazards include electric shock, solar radiation, drownings, noise, biological and ergonomic hazards, and slip/trip/falls, which can result in traumatic and soft tissue injuries, work-related musculoskeletal injuries (WMSDs), and others.[5,6] Further, bivalve aquaculture workers' risk perceptions may underestimate dangers associated with tasks, minimization of work-related pain, and attribution of "accidents" to human error rather than unsafe conditions.[7] Previous research highlights the need for organizational-level safety supports, including formal and context-specific occupational safety and health (OSH) training.[7]

A few studies have explored OSH in U.S. shellfish production. In Washington State,

CONTACT Caitlin A. Ceryes cceryes@towson.edu Department of Health Sciences, Towson University, 8000 York Road, Towson, MD 21252, USA
*at the time of contribution.

a secondary analysis of coastal shellfish workers' compensation claims (2006–2012) found high injury and illness rates. Reported injuries and illnesses included *Vibrio vulnificus* infections, non-viral conjunctivitis, eye injuries, work-related musculoskeletal disorders (WMSDs), and hand tool injuries.[8] A recent study by Dunleavy and colleagues[9] found Florida-based clam aquaculturists experience ergonomic hazards, chronic pain, and WMSDs, yet lack injury prevention resources.

U. S. shellfish aquaculture OSH research and gaps

Little primary research or surveillance exists to characterize conditions and hazards faced by U.S. shellfish aquaculture workers.[4] This is especially true for small-scale operations (defined as lacking on-site temporary worker housing and employing fewer than 10 non-family workers, annually), which are considered agricultural, and therefore exempted from national OSH reporting requirements and not represented in national OSH datasets.[10]

National data suggest injury and illness rates for U.S. aquaculture workers (5.6 per 100 full-time equivalents [FTE] in 2021) exceed Agriculture/Forestry/Fisheries (AgFF) sector rates (4.6 per 100 FTE) and average U.S. worker rates (2.9 per 100 FTE).[11] However, these rates are considered unreliable due to small U.S. aquaculture worker populations, suspected underreporting,[4] and aforementioned agricultural surveillance exemptions.[10] Considering these gaps, a 2016 policy analysis identified OSH as a major concern, given federal plans to expand the U.S. maritime aquaculture industry.[12]

Though the global literature base around shellfish aquaculture production is growing, the diversity of production methods and volumes, gear types, worker populations, and environmental settings contributes to gaps in context-specific OSH research, highlighting the need for primary investigations of hazards and safety methods.[4,13] Through this qualitative study, we aimed to engage directly with industry members and capture their perspectives in their own words. These insights not only highlight the current gaps in worker safety but also lay the groundwork for identifying opportunities to adopt strategies to meaningfully improve conditions and safeguard the well-being of those integral to this vital industry. This study gathered insights from Chesapeake Bay shellfish producers regarding: (1) operation characteristics; (2) injury/illness experiences; (3) risk perceptions; (4) safety interventions; and (5) needed interventions in shellfish aquaculture, to identify avenues for future research and intervention.

Chesapeake Bay shellfish aquaculture

The Chesapeake Bay is the U.S.'s largest estuary, bordered by the states Maryland and Virginia. It has brackish water of varying salinity levels, and averages 21 feet (~6 m) deep, with a maximum depth of 174 feet (~53 m).[14] Although operation numbers and volumes may reflect temporary COVID-19 pandemic-related impacts,[15] the Maryland and Virginia-based aquaculture industries are growing. Virginia produces the most oysters on the East Coast and the most hard clams in the United States.[16] Virginia's bivalve aquaculture operations decreased slightly from 194 to 178 operations between 2017 and 2022, but production values increased from $70.5 million to $93.5 million.[17] Maryland's small bivalve aquaculture industry almost doubled, increasing from 35 to 70 operations, between 2017 and 2022, with $11,463 million and $9 million in sales, respectively.[18] Although this growth has slowed in recent years, it aligns with global trends demonstrating increases in aquaculture-produced seafood for human consumption.[19]

Eastern oyster aquaculture growth methods include "off-bottom," "suspended" and "on-bottom," aquaculture.[20] In off-bottom culture, juvenile oysters grow in cages or bags on the intertidal zone sea floor. Buoys, racks, or frames attached to anchored lines hold these containers in place. Suspended production involves floating bags or cages off the bottom.[20] Production requires removing cages/bags, cleaning them, counting, separating, sizing, and "tumbling" the oysters, then returning them to grow-out sites.[21] This process increases growth and survival rates and repeats every few weeks until harvest or until growth slows.[21]

"On-bottom" culture resembles wild-caught methods after the seed production phase.[22] Growers "plant" seed directly on the sea bottom,[23] where the oysters grow undisturbed for years before harvesting using a dredge.[22]

Oyster production sites in the Chesapeake Bay are susceptible to biological contamination from pollution and runoff.[24] The Bay also contains naturally occurring pathogens, like, *Vibrio spp*., which proliferate in warmer waters[25] and can cause infections, septicemia, and gastroenteritis in humans.[26] While *Vibrio spp*. infections can be foodborne, aquaculturists can also develop skin, eye, or soft tissue infections from occupational *Vibrio spp*. exposures.[4] Climate change-driven increases in oceanic temperatures have seemingly driven increased *Vibrio spp*. infections from consuming seafood.[27] Shellfish producers in Maryland and Virginia abide by Food and Drug Administration (FDA) Hazard Analysis and Critical Control Point (HACCP) regulations to mitigate potential foodborne pathogen spread. HACCP curfews require that harvesting cease by 10 or 11 AM, when ambient temperatures rise during summer months.[28,29]

Methods

To answer our research questions, we adopted an exploratory, qualitative approach. By conducting semi-structured interviews with operators and worksite observations, we aimed to collect rich and detailed descriptions of hazards in operators' own words, and to include contextual and experiential aspects of work in this field.[30]

Recruitment

Recruitment occurred at a Maryland aquaculture industry meeting in November 2019 ($n = 5$) and through referrals from industry contacts ($n = 4$). The lead author recruited interested participants by phone or email and 100% agreed to participate. Interviewees were offered a $20 gift card incentive, but all declined. Interviews occurred in person or via telephone based on participants' preferences. Participants had to be over 18 years old, work in Virginia or Maryland-based shellfish aquaculture, and work 20 hours/week on aquaculture tasks. Recruitment and interviews ended in April 2020 due to the COVID-19 pandemic's impacts on the industry.

Interviews

The semi-structured interview guide (Appendix 1) was developed with input from industry members, aquaculture experts, and occupational health experts, and pilot-tested[30] with a shellfish aquaculturist in October 2019. The interview guide focused on: (1) operation and work descriptions, (2) injury and illness prevention and contributors, and (3) safety knowledge and interventions. Interviewees provided oral consent prior to interviews, which were audio-recorded. The Johns Hopkins University Bloomberg School of Public Health Review Board classified this study as category two, exempt.

Nine interviews were performed, averaging 75 minutes long (range: 52–110 minutes). Two occurred by phone, six at worksites, and one at a public library. Worksite interviews facilitated observation of work areas and equipment, but work tasks had always ended for the day.

Analysis

We used ATLAS.ti 24 – a qualitative coding software[31] – for data management and code application. We used a qualitative coding approach to categorize results and search for patterns and contrasts within and between interviews.[32] This approach facilitates interpretation by first assigning similar text passages to summative categories and sub-categories, which are then systematically re-examined and explicated as detailed narrative results.[32] First, two researchers conducted close-reads of interviews and developed a codebook that contained deductive codes based on the study's aims and interview questions and inductive codes capturing novel concepts identified by the researchers.[22] The final codebook contained 11 code groups (e.g., "injury") and 174 codes (e.g., severity, frequency, mechanism).[32] At the outset of analysis, both team members coded the same two interviews, followed by discussions to align their interpretations. To ensure rigorous and consistent coding, coders met frequently to discuss coding strategies, ensure code agreement, and maintained analytic memos.[32]

Following coding, code group results were exported to Microsoft Excel (Microsoft 365, version 2408) by code and synthesized into narratives answering the research questions.[32] Throughout analysis, constant comparisons identified within- and between-participant similarities and differences.[32] Current interventions were extracted and organized by the NIOSH Hierarchy of Controls model (Figure 1), which ranks safety and health interventions by effectiveness, with hazard elimination considered the most effective, followed by substitution, engineering, and administrative controls (e.g., policies, staffing), and using personal protective equipment (PPE).[33]

Results

Operation descriptions

All respondents owned or operated farms in the Chesapeake Bay. Almost all ($n = 8$) grew only oysters, and one grew oysters and clams. Table 1 contains demographics. Production methods included surface floats ($n = 1$), bags/cages ($n = 6$), bottom culture ($n = 1$), and a combination ($n = 1$). Five growers produced oyster seed. Respondents described seasonally variable daily work activities, with "grow-out" typically occurring between May and December. During grow-out, work could occur 12 hours per day, 6–7 days per week. While some growers harvest year-round, others mostly harvest from Thanksgiving to April.

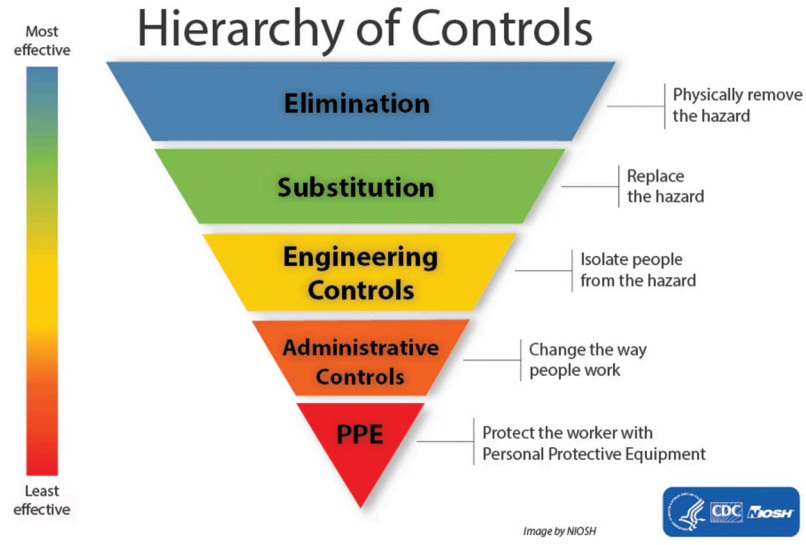

Figure 1. The National Institute for Occupational Safety and Health's (NIOSH) hierarchy of controls[33] ranks OSH interventions by effectiveness.

Table 1. Respondent ($n = 9$) and operation characteristics of Chesapeake Bay shellfish aquaculture operations by self-report, Nov 2019–April 2020.

Characteristic	Value
Estimated annual oyster production, range	100,000–1.25 million oysters*
Products, n	
Oysters only	8
Oysters and clams	1
Primary Growth Method, n	
Bags/Cages	6
Surface floats	1
Bottom culture	1
Combination of bottom culture, cages, floats	1
Years in operation, average (range)	8.5 (<1–20)
Oyster seed producer, n	5
Small business (≤10 full-time employees per year), n	9
Professional background in aquaculture or related sector,n	5

*One participant did not report annual volume.

All operations were small, with one to seven full-time employees and seasonal fluctuations in part-time, informal workers. Hiring informal workers (referred to as "day laborers" and local "blue collar" workers) during busy periods to meet production demands was described as relatively common. Operations averaged 8.5 years in business, ranging from less than one year to 20 years. Before starting their operations, five producers worked in related industries, including finfish or shellfish aquaculture or wild capture fisheries. Four producers transitioned from careers in unrelated sectors to aquaculture and initially lacked industry familiarity. These respondents took shellfish husbandry classes from agricultural extension offices, did their own research, and/or sought financial or technical assistance from state programs. These growers described a long trial and error period, with minimal outside guidance, to identify successful practices. One respondent explained: "I worked with [agriculture-extension] a bit… I ended up getting a loan from the state … but I never took any formal training… learned as I went, killed a lot of oysters."

All interviewees described creating their own production practices based on production goals, lease characteristics, and other needs. One participant explained, "Everybody makes up their own system based on the environment and what they're doing and their type of growing." In addition to planning tasks, most growers reported fabricating their own equipment to save money or because needed equipment was unavailable.

Work task mechanization varied. Some operators considered mechanizing systems ideal – for example, using winches and davits for lifting, or automating tumblers and sizing activities. Mechanization was considered important to maintain consistent production volumes in what one operator referred to as "an outdoor factory." Other respondents likened themselves to "vintners" producing artisanal, handmade products, uncompromised by mechanization.

Hazards

Table 2 summarizes results for hazards, injuries, illnesses, and hazard mitigation techniques observed or reported during interviews. Respondents reported exposures to ergonomic, biological, physical, and chemical hazards. Generally, conditions were described as "rough," challenging, and austere. One producer stated, "if you can't be hot, wet and dirty, [and] cold, wet and dirty, then you can't work for me."

Ergonomic

Tasks requiring repetitive work, heavy lifting, and awkward postures were described as common. Such tasks included lifting oyster cages (sometimes weighing over 100 lbs. [~45 kg.], dumping cages into sorters or tumblers, and loading bushels into

Table 2. Summary of hazards, related injuries/illnesses, and mitigation techniques reported/observed during interviews with Chesapeake Bay shellfish aquaculture operators ($n = 9$) between November 2019 and April 2020.

Hazard type	Hazard	Related injury/illness	Mitigation techniques*
Ergonomic	• Heavy lifting • Repetitive motion • Awkward positioning	• Work-related musculoskeletal disorders (WMSDs)	• Machinery to reduce loads • Team lifting policies • Work task rotation
Chemical	• Machine lubricants • Hydraulic fluids	• None noted	• PPE
Physical	• Sharp oysters • Sharp hand tools, equipment • Extreme weather • Slippery/wet/icy surfaces • Submerged working conditions • Equipment/vessel risks, including suspended equipment	• Lacerations • Slips/trips/falls on or from vessels or piers • Sprains/strains • Hypothermia • Falls overboard • Near-miss incidents	• PPE • Practice changes following close calls • Task-based training: often informal and infrequent • Weather-related work protocols • Ad-hoc safety assessments
Biological	• Waterborne pathogen exposures	• Wound infections	• PPE • Stocking first aid kits • Immediate wound care, like bathing arms in hydrogen peroxide • Worksite cleaning protocols

PPE, Personal Protective Equipment.
*Note: Table 3 provides in-depth mitigation technique summaries, categorized by the NIOSH Hierarchy of Controls model.

trucks for transport. For example, a respondent described, "Twist the wrong way picking up the bushel of oysters, it might be 75, 80 pounds [~31-–36 kg] … lifting half bushels at a time of seed, you're talking about maybe getting it loaded on a trailer, maybe 4,000, 6,000 pounds [~1800–2700 kg] loaded on … "

Chemical

Two people mentioned chemical hazards, including hydraulic fluid exposures and lubricating engine parts without wearing gloves.

Physical

Respondents reported exposures to sharp oysters and other objects; extreme weather (both hot and cold); submerged working conditions; equipment and vessels; slippery, wet, or icy surfaces; and others.

In terms of equipment and vessel risks, one respondent was almost crushed between a docking vessel and a piling, and another nearly dropped a 500-lb (~227 kg) float on a worker below. A third operator's overloaded vessel nearly capsized in bad weather. The participant using a dredge relayed several stories about other operators' masthead-mounted dredge cables snapping from weight or wear and nearly crushing workers. Those using davits and cranes stated that workers frequently stand underneath, creating a crush hazard.

Workers identified extreme heat, cold, and storms as potential dangers. Winter hypothermia risks included waterlogged conditions, falls overboard, or slips and falls from icy surfaces. Ice was an "easy way to get hurt," both because of slips/trips/falls, and because it can drag gear away into open waters. One operator sprained his ankle in icy conditions, stating, "I could see if I was by myself, hit my head, knocked myself out falling over or something, it would be bad… Hypothermia, the whole deal."

Biological

Respondents reported performing submerged work with open wounds and described exposures to pathogens as particularly concerning. As one respondent explained, "In our environment, it's really about cutting your hands and getting a *Vibrio* infection in your fingers."

Injuries & illnesses

Ergonomic injuries

WMSDs and chronic pain were described as so common, they were almost expected. For example, one respondent described wrist pain resulting from "carrying a bag of oysters that's 30 pounds [~13.5 kg] in each hand… 150 times in a day."

Contact with heavy objects

Multiple operators described heavy equipment hanging/swinging from overhead while aboard vessels and striking workers or, more rarely, pushing them overboard.

Lacerations

Respondents consistently described lacerations as the most common injury they encountered. One grower described his workers frequently incurring soft tissue injuries from rebar cages, knives, and oysters because "… they're around all kinds of stuff that might want to poke holes in them." All operators described oysters as dangerous, "basically a razorblade at its thinnest point.," that "cut your hands up pretty good." Lacerations also occurred when handling barnacle-covered equipment, dealing with sharp vessel components, and using knives. Laceration descriptions varied from "nothing serious" to requiring medical attention.

Slips/trips/falls

Several respondents reported serious incidents or close calls from falls off piers or vessels. One participant who fell while disembarking from a vessel incurred a laceration, stating, "I slid down the edge of a wooden board on a pier and … it filleted my leg and it was a 27-stitch wound." Reported fall contributors included icy conditions and wet, slippery work areas. *Wound infections*: Several respondents had either experienced a skin or soft tissue infection (SSTI) themselves or had a worker experience one. An operator described, "I had a guy last summer cut his leg pretty bad and get a bad infection from walking against a cage… had to get a couple of stitches." A few participants believed that rain

events and increases in water temperature could contribute to infection risks.

Injury risk perceptions

Operators consistently described occupational injuries as "part of the job" and downplayed risks, especially compared to those in wild-caught fisheries. When discussing injuries, respondents often attributed individual responsibility, describing those who were injured (including themselves) as "clumsy," "stupid," lacking common sense, and "dumb." Several operators expressed frustration with what they perceived as workers failing to mitigate risks. A manager explained, "I think getting hurt sometimes is directly proportional to how much attention that you pay, and …if you never pay attention … you're going to find yourself in an incident." Conversely, "toughness," "attention," "mindfulness," and "judgment" were considered protective against injuries.

Operators stated that risks increase when farmers are inexperienced; working alone or long hours; when the weather is "foul"; and when rushing to meet order deadlines, HACCP curfew, or to return oysters to the water. For example, the worker who cut his finger while freeing a line from a propeller said "… [that was] the last thing of that day and my error …[resulted from] mental fatigue…"

Hazard mitigation techniques

Respondents reported various hazard mitigation techniques. Table 3 details reported safety practices, categorized by levels of the NIOSH Hierarchy of Controls model.[33] Operators who discussed motivations for OSH interventions described wanting to decrease liability, maximize efficiency, and maintain high production volumes. One operator described: "if my people are hurt, and can't function, then they can't work and that tears up my [oyster production] mechanism." Several producers stated they desired more time, funding, or bandwidth to enact safety interventions on their operations; one explained, "I don't think, the motive or initiative is lacking. I think we just need to find the time."

Ergonomic hazard mitigation

Multiple interviewees wanted to or had already changed their equipment to reduce ergonomic risks. One respondent started out with a large, 1,500 lb. (~681 kg) bag system because they wanted high production volumes. They found the equipment so unwieldy and dangerous that they transitioned to smaller bags and cages that one or two people could lift. In contrast, one grower added cage weights, so they remained stationary in high winds.

While many operations had team lifting policies, worker rotation policies, and machinery to reduce loads, some respondents suggested they or their workers might "take a shortcut" and lift things themselves to save time. Respondents reported rarely seeking professional ergonomic injury treatment, and instead used "traditional" remedies (e.g., horse liniment) for pain or over-the-counter medications to keep working.

Mechanization was considered good mitigation for heavy lifting hazards, but a producer explained the downsides: "There's more risk…Instead of picking up that 25- or 30-pound [~11–13.5 kg] half bushel, now you're picking up 500 to 600 pounds [~226–272 kg] at a time…. It might be easier and all, but you definitely have to have more of a safety protocol." Less-mechanized operations also reported severe injuries from hand tools (e.g., puncturing a worker's hand while separating oysters with a screwdriver).

Infection prevention

Respondents reported prioritizing immediate care for scrapes and cuts. Cleaning methods included "bath[ing] their arms in hydrogen peroxide," pouring rubbing alcohol on wounds, and "bleach-[ing] everything."

Actions following close calls

Hazard mitigation sometimes followed close calls. One operator explained, "Nobody's interested in safety until somebody gets hurt." For example, one operator started providing sunscreen to his workers after having skin cancer treatment. Other producers noted that close calls were not enough to change activities or procedures due to the work's natural risks. A grower explained, "Close calls happen … Everywhere but an office, probably."

Table 3. Occupational safety and health (OSH) practices reported/observed at Chesapeake Bay shellfish aquaculture production sites November 2019–April 2020, ranked according to the NIOSH hierarchy of controls model.[33]

Hierarchy Level	Hazard type	Intervention
Elimination	Ergonomic	• Winches/cranes (e.g., a jet ski lift) • Trolley/baskets to push, not lift, oyster containers
	Weather exposure	• Enclosed vessel piloting area • Shade tent or move indoors
	Vessel-related	• Self-designed a barge to conduct sizing, cleaning, processing oysters at the lease, reducing trips from lease to shore • Stop using overhead boom attached to vessel mast, which can collapse and harm workers underneath
Substitution	Ergonomic	• Exchange heavy equipment (e.g., 1,500 lb. [~681 kg] cages) for lighter equipment (e.g., 40–80 lb. [~18–36 kg] cages)
	Lacerations & ergonomic	• Exchange sharp metal equipment for lighter plastic or mesh equipment
	Contact with equipment	• Exchange ropes/lines, with cables or chains • Replace overhead mast/boom for lifting with a trolley
Engineering	Ergonomic	• Add handles and bridles to cages/equipment • Lift tables to standing height
	Falls/slips/trips	• Install non-slip surfaces, vessel exit ladders • Install rope railings along platforms
	Contact with equipment	• Pad hard surfaces • Emergency winch stops • Reinforce winch/crane chains or cables to reduce strain under excessive weight
	Noise	• Insulate motors
Administrative	Ergonomic	• Use team lifting • Rotate workers between tasks • Restricting bag weight to 40 lbs. (~18 kg) • Stretching/yoga before work
	Working alone	• Use a "buddy system" • Text family/friends with expected location/time • Restrict lifting activities
	Biological	• First aid kits/wound cleaning agents on board vessels • Cleaning wounds immediately • PPE cleaning protocols (e.g., self-fabricated glove dryers to reduce bacterial growth)
	Weather	• Daily/hourly weather checks • Rotate workers away from lease sites impacted by wind/weather • Posting pre-established, upper tolerance wind vectors for leases • Harvest ahead/extra to avoid working on lease in bad weather • Designated warming areas, task rotation
	Slips/trips/falls	• Cleaning protocols
Personal Protective Equipment	Lacerations	• Gloves • Different gloves for winter, summer • Plenty available to change if gloves wear out • Boots • Goggles
	Noise	• Earplugs
	Radiation	• Sunscreen • Sunglasses • Hats
	Weather/ Overboard	• Foul weather gear • Pants and slickers • Dressing in layers • Waterproof coveralls ("oilskins") • Personal flotation devices (PFDs) • Wetsuits • High-visibility gear • Survival suits • Non-slip mats

Safety protocols

Most interviewees reported lacking formal safety protocols or standards. One operator described relying on his own task analysis: "There may be an OSHA book, but I've never read it… I simply rely on what do I see, and what keeps that person safe so he can continue to work for me on a regular basis." Safety decisions were commonly

considered "judgment calls," made by the owner/operators or the most experienced individuals.

While most respondents described ad-hoc safety practices and decisions as adequate and effective for managing safety risks, a few described challenges. One respondent described arguments about safety decisions among his business partners, due to differing risk tolerances. Another respondent described shifting risk assessments amidst economic pressures: "I think you start taking more risks with harvesting…. I know I have $2000 of revenue coming that will affect my decision if I'm on the fence or whatever."

Training

Employee safety training was described as occurring infrequently, if at all. If provided, training was typically informal or not required. One operator described, "[I] walked through the process myself for the other people, sort[ed] out what I think's appropriate, try to teach that to somebody, and as new employees get hired that institutional knowledge sort of gets passed down." Producers explained that training day laborers is unfeasible due to high turnover rates: "I'd be lying if I said new guys get a safety lesson. I go through so many people, it's really if you show up, you got a job."

Suggestions to support safety efforts

No interviewee had encountered formal OSH training or resources. Though many operators knew about or used state or federal industry programs supporting aquaculture businesses, they noted that no program provided resources about OSH. Most growers desired information about common hazards and effective mitigation strategies. Several producers stated that ideal supports would be easily accessible, include industry input, and either not incur extra work or help reduce their workloads. Importantly, some respondents emphasized that they oppose any new aquaculture worker safety regulations.

Training

Operators' ideas for training included task-specific information for new aquaculture workers, basic first aid and CPR training, information about safely mechanizing tasks, and details regarding workers' compensation insurance coverage. One grower suggested distributing "…kind of like a canned piece of literature that all farms could use," noting that while farms differ, they share risks like hypothermia and *Vibrio* exposure. In contrast, a few producers noted their employees "wouldn't take [training materials] seriously." Less experienced operators stated they would welcome learning safety information from others, though this presents challenges, given proprietary production methods and equipment.

Workshops/seminars

Several respondents viewed safety workshops as undesirable, and would not attend, though others said they would if they were accessible (i.e., located centrally, remote or recorded, cost-free), relevant to their specific needs, or combined with existing workshops. One respondent suggested a safety workshop with attendance benefits, like reduced workers' compensation rates. Another respondent suggested modeling seminars on required HACCP seminars, where participants learn about hazard prevention and develop individualized operating procedures and policies.

Safety gear

Producers acknowledged needing basic first aid kits on hand but lacked time to prepare and refill them. Some suggested that they would use kits from trusted organizations and appreciate reminders or help refilling them. Others desired funding support or free schematics for safety gear fabrication.

Discussion

This qualitative study used semi-structured interviews to characterize risks and hazard mitigation techniques among Chesapeake Bay aquaculturists. These findings contribute to global efforts to better characterize OSH risks and enhance OSH efforts within the fast-growing aquaculture sector (for example, in Australia,[34] Canada,[5] Norway,[35] Brazil.)[6,7] These results are particularly important in the United States context, as limited OSH evidence exists to inform safety interventions amidst concerted efforts to increase coastal and marine aquaculture production,[4] and current national injury and illness surveillance systematically

excludes many small-scale aquaculture farms.[10] The findings on safety precautions and the need for additional research to protect workers may translate to other countries with similar industries.

Our results suggest injuries and illnesses on small U.S. aquaculture farms are common and that many incidents go unreported. Operators reported various hazards, including ergonomic, physical, chemical, and biological risks, which align with findings from other seafood worker populations.[5,34,36] Reported work-related injuries and illnesses included lacerations, wound infections, falls, WMSDs, and contact with objects, which are also reported elsewhere.[5,34,36] Currently implemented interventions span the hierarchy of controls, with administrative controls and PPE most reported. Most operators were interested in safety information and provided suggestions for workshops, training, and safety gear provision.

Our findings aligned with Guertler and colleagues' findings that aquaculture workers may regard injuries and chronic pain as unavoidable, lack formal training, and downplay workplace risks.[7] Further, interviewees noted that less experienced operators or those transitioning from unrelated industries may lack knowledge of work tasks, piloting vessels, and other skills that could increase safety risks relative to those with industry experience. These same businesses lacked resources and funding for safety interventions and training, which is common for small businesses, and associated with high injury rates.[37] Many operators used state or federal industry programs to start or improve their businesses, which could provide safety-related guidance and funding and capacity building for safety upgrades and training.

Reported hazards were diverse, reflecting the varied production methods, tasks, and equipment used by operators. Researchers have noted previously that such variability creates challenges for creating standardized interventions or best practices.[4] Myers and Durborrow[13] suggest identifying low-cost, feasible, and scalable interventions, by documenting and sharing interventions already in use. Hosting conversations for growers to share safety techniques could be a low cost, low-effort intervention, as many growers already engage with professional networks. Such information could especially benefit novice operators. Especially if combined with needed regulatory changes, like increased injury, illness, and near-miss reporting requirements, such interventions could serve to improve conditions across the industry.[38]

Growers use interventions across the hierarchy of controls, and report mainly administrative controls or PPE. This finding is expected, as such strategies can be low-cost and implemented easily. We cannot comment on intervention implementation frequency or quality, but these findings echo Dunleavy and colleagues' that aquaculturists preferred individualized, self-managed chronic pain and WMSD reduction strategies, like positioning adjustments, rather than time- or resource-intensive interventions, like task rotation or team-based lifting.[9] However, implementing upstream interventions that "design out" potential risks can be more impactful, especially in developing aquaculture industries like in the U.S.[39] Given operators' reported challenges in finding time to address OSH risks, resources should focus on identifying and implementing such higher-level interventions.

Respondents, who can spend many hours in waterlogged conditions with soft tissue injuries, voiced concerns about wound infections. Indeed, increasing concern exists regarding waterborne pathogens in the Chesapeake Bay and mid-Atlantic regions.[40] Research is needed to characterize *Vibrio spp*. and other waterborne infection prevalence and identify prevention strategies for workers.

Our findings align with other studies suggesting that sleep deprivation and fatigue may contribute to work-related injuries, especially in the agriculture, forestry, and fisheries sectors.[41] We echo calls to better characterize the relationship between injuries and fatigue at work.[41] Aside from long work hours, mental fatigue, piece-rate payment, and seasonality, we also suggest that HACCP food safety regulations, which limit shellfish harvesting hours per day in the summer, could create conditions for rushed work and increased injuries, or exacerbate sleep deprivation and fatigue.

Strengths and limitations

To our knowledge, no other study examines OSH challenges in Chesapeake Bay shellfish aquaculture. The interviews generated highly detailed information across multiple production methods

and characterized various hazards. The small sample size represents a key limitation. This research occurred in late 2019 and early 2020. We attempted to continue recruitment during the COVID-19 pandemic, but major industry impacts like closures, furloughs, and stress made it unfeasible. Our sample size falls within a range where saturation is possible,[42] and we believe we achieved it for the hazards and challenges facing small-scale shellfish aquaculture producers. Our rigorous analysis, including double coding, enhances our findings' credibility. As in all qualitative studies, generalizability beyond the study context is limited. We cannot comment on prevalence of the hazards, injuries, illnesses, and interventions reported here, though our results provide important information for quantitative studies to establish such estimates.

Conclusions

Significant opportunities exist to reduce hazards, injuries, and illnesses among U.S. shellfish aquaculture producers, and industry growth and sustainability requires such advances. Like other developing aquaculture industries, this study found that small-scale Chesapeake Bay shellfish aquaculture producers face significant OSH challenges, with limited safety resources and guidance. Many operators considered injury and illness unavoidable, and many respondents had experienced or witnessed work-related injuries. Reported safety interventions span the hierarchy of controls, and skew toward administrative control and PPE categories, potentially revealing a need for upstream, design-based interventions. Respondents suggested that safety interventions should be developed with industry input, highly accessible, and address both common and severe safety challenges.

Governmental industry development support should include funding for robust and industry-inclusive OSH surveillance and interventions, concentrating on the most effective hazard control measures, including elimination, substitution, and engineering controls. By characterizing shellfish aquaculture producers' experiences with hazards, injuries, and illnesses, and reporting current and desired interventions, we provide important future research avenues to enhance safety and health within the East Coast shellfish aquaculture industry and highlight potential similarities with other developing aquaculture industries, worldwide.

Acknowledgments

Thanks to the participants and the Maryland Aquaculture Council and Virginia Institute of Marine Science for guidance and assistance with recruitment. We also thank Don Webster, Jennifer Lincoln, and Steven Harvey for sharing their expertise and time to support this project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The funders had no role in study design; data collection, analysis, or interpretation; preparation of the manuscript; or decision to publish. CAC was supported by the Johns Hopkins Center for a Livable Future-Lerner Fellowship and the Dr Winnifred Hayes scholarship. CAC and EEM were supported by a training grant from the National Institute for Occupational Safety and Health grant # T42 OH0008428. ERHM was supported by the National Institute of Environmental Health Sciences Training Program in Environmental Health Sciences grant # T32ES007141.

Data availability statement

Data will be made available upon reasonable request.

ORCID

Caitlin A. Ceryes http://orcid.org/0000-0002-8620-1991

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Appendix 1: Semi-structured Interview guide deployed between June 19–April 2020 to interview shellfish aquaculture operators

Note: *The following was used to guide conversation, and not read or followed, verbatim.*

Section 1. Section introduction & work tasks

Thank you for sitting down to talk with me. I want to start by hearing about your work at your operation and your background in shellfish aquaculture. Then I'll go into questions about your views of safety and health in shellfish aquaculture. I don't work in this space, so please tell me all the details, even things that don't seem important. If it helps you can pretend like I'm a new employee or pretend like you're explaining things to your mom.

(1) What is your job title and main job responsibilities?
   a. *If a worker:*
      (i) What does a normal day look like to you?
         (1) *Prompt*: what did you do yesterday?
      (ii) Are you full-time or part-time?
      (iii) Are you seasonal or year-round?
      (iv) How much time during an average day would you say you spend in water?
   b. *If an operator*:
      (i) How many workers do you have at your operation?
      (ii) Does the number of workers change by season?
(2) What is your background in the aquaculture industry?
   a. How long have you been involved in shellfish aquaculture production?

Section 2. Injury and illness prevention

Now I'm going to ask about how you keep yourself safe while doing your job. The reason why I'm asking about this is because we know a lot about what land farmers deal with, and some about what fishermen deal with, but we don't know much about what kinds of hazards aquaculture workers face to put shellfish on the table. Your answers here are confidential and will be added to a group of answers from all over Maryland and Virginia. I'm not asking to get anyone in trouble, and participation in this study is completely confidential. Without this information it's hard to know what kinds of education or safety mechanisms would be helpful in aquaculture production.

During these next few questions, it might be helpful to think about the different activities you do while working, and different tools you use.

(1) Have you ever been hurt on the job while doing shellfish aquaculture work?
   a. *If yes*, please describe.
      (i) *[for interviewer: prompt to obtain mechanism, nature, time away from work, part of body, medical treatment.]*
   b. *If multiple instances*: Please tell me about the most recent incident you can think of, and the most severe you can think of
(2) Have you ever been present when a co-worker got hurt on the job?
   a. *If yes*, please describe.
   b. *If multiple*: Please describe the most recent and the most severe.
(3) What are common ways a worker could get hurt while doing shellfish aquaculture work?
   a. In your experience, how common is it to be hurt while doing shellfish aquaculture work?
      (i) Have you seen any changes in how often people get hurt over your shellfish aquaculture career?
(4) Do people get formal medical treatment (E.g. doctor or hospital visit?) when they get hurt?
   a. what's the threshold for going to the hospital?
   b. If not, what do you think are the reasons why people might not go?
(5) Have you ever heard about a "close call," where an accident almost happened but was avoided, at your farm or any other facility?
   a. *If yes*, please describe.
   b. *If multiple*: Please describe the most recent and the incident that could have been most severe.

We're interested in hearing about different situations or factors that may change workers' risks of getting hurt or sick on the job.

(6) Do you think specific conditions or factors change the risk getting hurt or having an accident?
   a. *if yes*: How?
      (i) *Prompts*:
         (1) Do different farming techniques or species change injury risk?
         (2) Do worker characteristics change injury risk?
         (3) Do farm characteristics change injury risk?
(7) Do wounds (e.g. getting a cut or a pin-prick) occur during your work?
   a. *If yes*, how often?
   b. What is the typical care a worker would receive for a wound/broken skin on the job?
   c. How often do wounds get infected?
(8) *For operators*: Across the entire shellfish aquaculture industry, what work tasks are most dangerous? Why?
(9) *For workers*: Of all of the tasks you do/have done to produce shellfish, which do you think were most dangerous to you?

Section 3. Contributors to injuries/illnesses

Now I'm going to ask questions about outside forces that might change your habits or work patterns. For example, it's common across work settings for time pressure to increase work-related stress and change work patterns. I am interested in hearing about how outside forces, like time constraints or weather conditions, might affect workers' safety practices in shellfish aquaculture. When I say "safety practices," I mean wearing protective equipment, or using certain techniques or machinery. You can talk about anything workers do to keep safe on your farm.

(10) First, I'll start with the question: Do you think anything increases the risk that you will get hurt or sick in the course doing of your work?
(11) How does weather (e.g. extreme heat or cold, storms, high tides) impact your work?
   a. Have you ever had to change the way you work because of weather?
      (i) *Prompt*: Does the weather ever prevent you from doing your planned work?
         (1) *If yes*:
            a. In what way?
            b. *Prompt*: for example, would you wear more protective equipment; move tasks to a different day; take more or fewer people with you; change your work pace?
            c. *Prompt*: are there policies for weather or is it more based on personal comfort with weather challenges?
            d. *Prompt*: Are people ever expected to perform despite being worried about safety due to the weather?
   b. Have you noticed trends or changes in weather or extreme weather events that affect your work?
(12) How do time constraints affect your risk of injury, from your perspective?
   a. *If an operator*: Do you worry about workers getting hurt when they are working under time constraints? Why?
   b. *If a worker*: Do you worry about increased risk of getting hurt for you or your co-workers when working under time constraints? Why?
(13) Are there any other factors that impact your safety that we have not already discussed?

Section 4. Safety knowledge & future interventions

Now I'll be focusing on safety interventions you might be familiar with, or ideas for improving shellfish aquaculture safety information sharing and knowledge.

(14) At your operation, who is "in charge" of keeping workers safe, or most responsible for preventing injuries and work-related accidents?
   a. *Prompt*: This could be the workers, themselves; owners/leaders; rules or policies; shift managers, or any combination.
   b. Has your operation fabricated its own safety equipment or made other changes to prevent injuries or accidents?
(15) What do you think is your current level of knowledge is about maintaining your own/your workers' health and safety in shellfish aquaculture?
   a. What do you need to fill gaps in your (or others') safety knowledge at your workplace?

(i) *prompt*: examples would be workshops; round-table conversations; drills; establishment of performance indicators or inspection criteria; or meetings with other producers/workers be helpful to you or your operation?

(16) Are there any injury or wound/infection prevention methods you have thought of or heard about that you would like to use on your operation?

(17) Do you think you or other shellfish producers would be open to learning about workplace safety by engaging in workshops, discussions, or other interventions specific to shellfish aquaculture?

(18) *If an operator*: Have you ever talked with an attorney or other specialist about managing workplace risks through strategies like insurance, contracts, or worker protections?

Wrap-up

(19) We are trying to make this work as relevant and useful to aquaculture workers as we can. Is there anything else we have not discussed that you think is important to share about aquaculture worker safety and health?

a. Is there something I should have asked you that I didn't ask you?

Thank you so much for your time.