Dena Ali,[1*] Jeffrey M. Farber,[1] JinHee Kim,[2,3] Naghmeh Parto[2] and Ray Copes[3]

[1*]Canadian Research Institute for Food Safety, Dept. of Food Science, University of Guelph, Guelph, Ontario, Canada. N1G 2W1
[2]Public Health Ontario, Toronto, Ontario, Canada M5G 1V2
[3]Dalla Lana School of Public Health, University of Toronto, Toronto, Ontario, Canada, M5T 3M7

PEER-REVIEWED ARTICLE

Food Protection Trends, Vol. 41, No. 3, p. 293–304

2900 100th Street, Suite 309, Des Moines, IA 50322-3855

A Qualitative Risk Assessment of Liquid Nitrogen in Foods and Beverages

ABSTRACT

Smokey liquid nitrogen (LN_2) infusions are one of the latest eye-catching food trends. With its ability to create fog-like effects and flash freeze foods, LN_2 has become popular for use in ice cream, snacks, and cocktails recently. Although perceived to be harmless, there are incidents of consumers suffering adverse health effects after consuming foods prepared with LN_2. Thus, a qualitative risk assessment was undertaken to estimate the potential risks to consumers. Through an analysis of gray and scientific literature, case reports related to inhalation, ingestion, and contact with LN_2 were reviewed for relevant information. It was found that inhalation of LN_2 vapors could potentially cause rare, but serious, injuries such as respiratory distress and asphyxia. Ingestion injuries, which typically result after consuming LN_2 before it fully evaporates, often include gastrointestinal barotrauma and rupture. Lastly, when skin or tissues come in contact with LN_2 for more than a short period of time, frostbite can occur. To reduce the risks posed to consumers, it is recommended that (i) vendors are properly trained to handle and serve LN_2, (ii) patrons are given clear instructions on how to safely consume such treats, and (iii) regulatory agencies put appropriate regulatory interventions into action as needed.

INTRODUCTION

Ambient air is composed of approximately 78% nitrogen gas *(26)*. Through a process called fractional distillation, nitrogen gas in the air can be separated from the other components of air and converted into its liquid state *(3, 26)*. Nitrogen in its liquid form is referred to as liquid nitrogen (LN_2) and is characterized as being inert, colorless, noncorrosive, and nonflammable *(1, 26)*. For nitrogen to remain in its liquid state, it must be kept at very high pressures and extremely low temperatures *(3)*. If LN_2 comes in contact with anything above its boiling point (−196°C or −320.1°F), it will transform back into nitrogen gas *(3, 26)*.

Due to its cold temperature, LN_2 has become widely adopted for its rapid cooling and freezing applications *(38)*. From flash freezing foods to preserving biological specimens, LN_2 serves many different functions in various industries

*Author for correspondence: Phone: +1 519.982.3767; Email: alid@uoguelph.ca

(38). Thus, its use has been well documented in industries such as health care, sports, rubber and plastics, research, construction, music, electronics, food and beverage, automotive, and pharmaceutical and metal manufacturing *(1, 38)*.

Dry ice, known as solid CO2, is often confused with LN_2. However, when LN_2 reaches its boiling point temperature of −196°C, it undergoes vaporization (transition from liquid to gas) *(3)*. In contrast, dry ice undergoes sublimation (transition from solid to gas) when it reaches a temperature of −78.5°C *(3)*. Although both can be used for cryogenic applications, different industries prefer to use one over the other depending on their temperature requirements, costs, and ease of use. In retail food settings, LN_2 tends to be used more often than dry ice, which is why this paper primarily focuses on LN_2.

In the food and beverage industry, the commercial use of LN_2 as a coolant is well established *(3)*. It is an ideal freezing agent because of its ability to reduce chemical and microbial spoilage in foods and beverages, while retaining optimum flavor and quality *(1, 34)*. This is accomplished by using the cold temperature of LN_2 to help slow heat production and oxidation during processing, packaging, and shipping *(3)*. Besides chilling to prolong the shelf life of various foods like meats, dairy products, produce, condiments, sauces, and desserts, LN_2 also has many other applications *(3)*. These include adding pressure to bottled and canned beverages to allow for stronger and more rigid packaging, using freezing processes to grind meats and spices, and speeding up cooling during product layering to prevent the blending of constituent parts *(3, 18)*.

Apart from using LN_2 as a food processing and preservation aid, retail food and beverage establishments are now capitalizing on trends that involve using it in more unconventional ways. Such trends include applying LN_2 to foods or glassware just prior to consumption, to create aesthetically pleasing smoke-like effects and novelty frozen desserts like ice cream in an instant *(3, 36)*. Such effects occur because LN_2 is extremely cold, and it produces a visible fog upon evaporation in warmer air settings *(2)*. This method of combining scientific techniques with culinary art to prepare and present food is sometimes referred to as molecular gastronomy *(3, 8)*. Culinary applications of LN_2 include flash freezing foods and liquids to create garnishes, crafting unique shapes out of food, improving cooking processes, manipulating textures, and enhancing visual appeal *(3, 8)*.

To consumers, these novelty foods and beverages seem like harmless fun. However, there is limited awareness about the potential health risks LN_2 poses to consumers if foods or liquids are served directly after the application of LN_2. When used in manufacturing as a processing aid, the risks are minimal because, by the time the product reaches the consumer, it is no longer as cold and the LN_2 has fully evaporated *(36)*. However, that is not always the case when it is applied to desserts and drinks at the point of purchase. Consequently, case reports are now emerging of patrons suffering acute, sometimes severe, injuries after improper ingestion of LN_2. Therefore, from a public health perspective, research on this topic is important to identify and reduce any risks that may impact the health and well-being of consumers. To evaluate the likelihood of risk associated with LN_2 consumption, a literature review and qualitative risk assessment was performed.

METHODS

The focus of the search strategy for this systematic review was to identify, extract, and analyze data from the literature that was most relevant to LN_2 consumption. This began with a comprehensive search for scholarly publications and clinical case reports in the databases Ovid MEDLINE, Web of Science, and TOXNET. An Internet search on Google Scholar was also performed to obtain additional scholarly resources on LN_2. These searches were conducted using the following key words, truncations, and Boolean operator combinations: ("liquid nitrogen.m_titl.") AND ("drink*.ti,ab." OR "beverage*.ti,ab" OR "cocktail*.ti,ab."), ("ingestion*.ti,ab." OR "consumption*.ti,ab." OR "inhalation*,ti,ab."), ("injury*.ti,ab." OR "risk*.ti,ab." OR "danger*.ti,ab." OR "effect*.ti,ab."), ("frostbite*.ti,ab."), ("asphyxiation*.ti,ab."), ("ice cream*.ti,ab." OR "snack*.ti,ab,"), and ("barotrauma*.ti,ab." OR "gastric perforation*.ti,ab." OR "pneumoperitoneum*.ti,ab."). A more detailed outline of this search strategy can be found in Appendix A. Because studies on LN_2 consumption are limited, search restrictions on language, geographical location, experimental design, and dates were not applied. Cases of LN_2 exposure via inhalation, ingestion, or physical contact in nonfood settings were also reviewed for relevant information. When non-English articles that were related to LN_2 consumption were found, Google Translate was used to interpret the findings into English. Additional articles were also found by scanning through the reference sections of articles identified in the search. Furthermore, to address potential research gaps and gather additional evidence on LN_2 consumption, gray literature sources were also reviewed. These resources were retrieved from Google using various combinations of the following search terms: "liquid nitrogen," "treats," "snacks," "ice cream," "cocktails," "dessert," "dangers," "risks," "regulations," and "national/international food surveys." Due to the plethora of search results generated, information was only collected from the top 100 search results. They consisted of national and international food policy statements, government publications, newspaper articles, statistical reports, and other Web-based publications. See Appendix B for more information regarding the websites and databases used to retrieve gray literature. Overall, a total of 43 peer-reviewed and non-peer-reviewed sources were synthesized for this review.

HAZARD IDENTIFICATION

Although it is not common for LN_2 to be applied to foods and beverages immediately before consumption, this practice has been gaining popularity in recent years *(3, 36)*. Thus, case reports of people suffering from food-related injuries are beginning to appear *(3, 36)*. Whereas cases are still rare, some of the injuries being reported have been quite severe, making this food trend a major cause for concern. Despite limited research in this area, this review of the literature revealed several health outcomes that may be associated with improper ingestion and handling of LN_2. These are described in further detail in the following subsections. Although not all of these have been associated with exposure through foods and beverages, they provide information that is helpful in reducing possible LN_2 risks to consumers and food handlers.

Potential health outcomes associated with LN_2 inhalation

Nitrogen gas is a simple asphyxiant *(26)*. In the event of a spill or leak in an enclosed area at room temperature, LN_2 will evaporate and displace some of the oxygen in the air *(3, 26)*. Without proper ventilation systems in place, individuals can become oxygen deprived if nitrogen levels in the air surpass 88% *(26)*. This can lead to asphyxiation and is very dangerous because it may occur without warning and may potentially result in death *(19, 20, 25)*. Although this is not a risk for consumers, it may be a risk for food handlers working with large amounts of LN_2 in a small room.

Potential health outcomes associated with LN_2 contact

LN_2 can cause severe thermal damage to the skin, eyes, and internal organs if not handled safely *(26, 31)*. Examples of thermal-related injuries that may result following contact with LN_2 include frostbite, blisters, ulcers, edema, and tissues necrosis *(9)*. However, the severity of injury is dependent on the duration and area of contact. In most cases, injury occurs when bare skin and other exposed tissues come in contact with LN_2 for more than a few seconds *(26)*. For example, this can happen if individuals hold LN_2-coated treats in their mouths for too long, or if the snack sticks to their gums. In other instances, individuals can be fully covered and wearing protective gloves but can still end up with thermal injuries after handling or working with LN_2 *(31)*. Thus, both direct and indirect exposure to LN_2 should be avoided to prevent injury.

Brief contact with small amounts, e.g., 2 to 3 mL of LN_2, however, does not always result in cryogenic injuries *(2, 3)*. The reason for this has to do with a phenomenon called the Leidenfrost effect *(2, 15)*. To illustrate this effect, one can envision LN_2 as a droplet encountering a surface with a temperature far above its boiling point *(7)*. When this occurs, the LN_2 rapidly starts to evaporate and pressure from the vapor builds up as it tries to escape from beneath the droplet *(7)*. At a certain level of pressure, the vapors elevate the droplet, forming an insulating film of vapor between the droplet and the surface *(2, 3, 7)*. As a result, this insulating film creates a barrier between the two surfaces, which causes a reduction in thermal transfer and injury *(2)*.

Potential health outcomes associated with LN_2 ingestion

When LN_2 is added to desserts and drinks immediately before consumption, the belief is that it will evaporate and, therefore, pose no harm to customers *(36)*. Unfortunately, this is not always the case because sometimes there will be residual LN_2 that remains on the bottom of a serving container *(11)*. In addition, LN_2 is tasteless *(26)*. Thus, if consumers are not instructed to wait before the LN_2 completely vaporizes, they might accidentally ingest it without realizing it *(3)*.

The most serious injury faced after ingesting LN_2 is gastrointestinal barotrauma, which develops due to an increase in pressure within the stomach *(2, 10, 21–23, 30, 41–43)*. This occurs because, when LN_2 enters the body, it immediately begins to evaporate upon contact with surface temperatures higher than its boiling point *(39)*. Furthermore, as the LN_2 travels from the mouth to the esophagus and into the stomach, the vapors that form along the way can lead to a large increase in pressure *(39)*. The reason for this is that LN_2 has a liquid-to-gas volume ratio of 1:694 *(2, 30)*. This means that, when LN_2 evaporates, its volume will increase by about 700 times within the body. As a result, patients may experience severe and painful abdominal distension following ingestion, because of the increase in volume and pressure within the gastrointestinal tract. *(2)*. This rise in pressure typically leads to tissue necrosis and gastric rupture in the lesser curvature of the stomach, which requires surgery to fix *(30)*.

Potential health outcomes associated with biological contamination

LN_2 can also serve as an effective storage medium for pathogens *(29)*. Microorganisms that can potentially survive after being cryopreserved by LN_2 include bacteria, fungi, yeasts, and viruses *(29, 35)*. Examples of microorganisms that have been found in LN_2 tanks used to store biological specimens include *Escherichia coli, Bacillus cereus, Mucor* spp., *Staphylococcus* spp., and *Pseudomonas aeruginosa*, some of which can be spread through unhygienic practices *(29)*. Although there have not been any reported incidents of consumers coming into contact with biological hazards from LN_2 in their foods and beverages, it is still a potential hazard.

HAZARD CHARACTERIZATION

Given its relatively new applications in the retail food and beverage industry, no definitive dose-response relationships have been established for ingesting, inhaling, or coming into contact with LN_2. However, based on the data available, it is apparent that the severity of injury is dependent upon the duration and area of contact, as well as the volume of LN_2 one comes into contact with. For example, larger amounts of

LN_2 and longer contact times are more likely to be associated with more severe injuries. The following sections provide more information on the relative doses needed to elicit a response after ingestion, inhalation, or physical contact with LN_2.

Ingestion

Almost 80% of the case reports related to LN_2 ingestion did not identify the quantities of LN_2 consumed. Among the few that did, subjects who suffered gastric perforations after LN_2 consumption ingested anywhere from 15 to 30 mL of LN_2 *(2, 22, 41)*. Given the limited number of reports, there is considerable uncertainty regarding how much LN_2 would need to be ingested to produce injury.

Inhalation

In all of the cases of thermal injury due to LN_2 inhalation, the dose levels were not provided. In general, anyone is susceptible to asphyxiation once sufficient amounts of LN_2 evaporate and cause oxygen levels to fall below 12% *(19)*. However, when it comes to other inhalation-related injuries like asthma attacks, not everyone will experience distress to the same extent. Thus, whether or not LN_2-induced injuries will occur depends on the dose, an individual's health status, and the environment in which it is inhaled.

Physical contact

Likewise, many of the studies describing cases of external or internal contact with LN_2 (e.g., touching LN_2 with one's hands or tongue) also did not make any reference to dose levels. However, a common theme observed was that injury severity was more dependent on the duration of exposure to LN_2 rather than the extent of LN_2 contact.

Exposure Assessment

Potential sources of exposure

With the help and influence of social media, consumer interest in LN_2-infused foods has been on the increase. As a result, a variety of food and catering establishments such as restaurants, shopping centers, kiosks, bars, nightclubs, festivals, and fairs now offer these desserts and beverages *(3, 36)*. Some of the more well-known treats and beverages prepared with LN_2 include fog-emitting cocktails, instant ice creams, and billowing smoke snacks comprised of cereal puffs, donuts, or cookies, commonly referred to as Dragon's Breath, Heaven's Breath, or Nitro Puffs *(3, 36)*. LN_2 can also be used to create garnishes from fresh herbs or berries, prevent the overcooking of burgers, and prepare a variety of other smoke-emitting dishes *(12)*.

Prevalence and populations exposed

Due to how popular these LN_2-infused specialty desserts and beverages have become, they are now being served worldwide, but primarily in larger cities *(3, 9, 21, 30)*. Although there is widespread potential for exposure to LN_2-infused foods and beverages, some age groups will come into contact with certain food products more than others. For example, whereas LN_2-infused ice creams and snacks are available to the general population, they typically appeal more to children, adolescents, and young adults, and only adults would be permitted to drink alcoholic beverages made with LN_2 *(21, 27, 30)*.

Likelihood of exposure

At present, comprehensive data on the use of LN_2 served in retail food and beverage settings are nonexistent. To estimate the likelihood of exposure to foods that may be prepared with LN_2, general food consumption patterns in Canada and the United States were analyzed. When Americans were asked to partake in a "24-hour dietary recall" for the 2015 to 2016 National Health and Nutrition Examination Survey, the percentage of cereals, baked goods, ice creams, and beverages being consumed was less than 10% for each *(6)*. Because only a relatively small percentage of these foods are likely to be prepared using LN_2, the number of people or percentage of the population exposed is likely to be small. Moreover, according to the 2014 to 2015 Canadian Foodbook Report, people tend to consume ice cream and cereals more frequently during the warmer months of the year *(16)*. Because these treats are often served cold, exposure is estimated to be higher during the warmer seasons than the colder seasons *(16)*. In addition, many of these novelty foods are often sold at pop-up events or annual festivals, which implies that consumers who do consume these treats would not do so very often *(13, 14)*. However, the probability of exposure will vary depending on the region because some business chains run all year long and are typically located in major cities.

Note that the survey findings used for this analysis might not be an accurate representation of the entire population because the food consumption histories would have been subject to recall, response, and proxy bias. In addition, individuals without a landline or cell phone number (e.g., individuals in correctional institutions) were excluded from the telephone surveys and were, thus, not accounted for. Nevertheless, because very few establishments actually serve these specialty treats, the overall exposure to LN_2-infused foods is presumed to be low. Although individuals may also be exposed to LN_2 in nonretail food settings (e.g., schools, homes, etc.), these types of encounters are very rare *(23, 43)*. Additionally, LN_2 is not readily available for purchase at most stores because very few specialty retailers and distributors sell the agent.

Summary of adverse effects attributable to LN_2-infused foods and beverages

A total of nine peer-reviewed and eight non-peer-reviewed reports related to LN_2 consumption were found and summarized in *Tables 1 and 2*, respectively. Among the 17 cases, 10 resulted in gastric perforations and eight in cold burn injuries; seven cases reported experiencing respiratory difficulties.

TABLE 1. Peer-reviewed case reports of LN_2 exposure and/or consumption

Case #	Setting & Location	Case Type	Sex & Age (Years)	Details of Incident	Clinical Manifestation	Reference
1	School – *United States*	Ingestion	Male – *15*	Subject ingested approximately 30 mL of LN_2 while preparing ice cream during a science experiment.	• Seizure • Distended abdomen • Massive pneumoperitoneum • Minimal pneumomediastinum • 10 cm perforation (lesser curvature of stomach) • Tissue necrosis near perforation	*(2)*
2	N/A – *Australia*	Ingestion	*Female – 30*	Subject placed cookie coated with LN_2 in her mouth and blew on it to produce a "cauldron-like" effect before consuming it.	• Mild burning sensation in the mouth • Second-degree intraoral frostbite that resulted in blisters and ulcers in the lower labial mucosa	*(9)*
3	Amusement park – *Asia*	Ingestion	Male – *13*	Subject ingested a cookie that had liquid nitrogen applied to it.	• Severe abdominal pain • Distended abdomen • Shortness of breath • Heart rate: 120 beats/min • Large volume pneumoperitoneum • Abnormal white blood cell count (21,400/μL) • Multiple erythemas (lesser curvature of stomach) • 4 cm perforation (lesser curvature of stomach)	*(21)*
4	N/A – *Europe*	Ingestion	Male – *28*	Subject ingested 15 mL of LN_2 in an attempt to "produce an impressive burp."	• Severe abdominal distension • Subcutaneous emphysema • Gastric rupture (lesser curvature of stomach)	*(22)*
5	School – *United States*	Ingestion	Male – *13*	Subject ingested a smoke-emitting blend of orange crystals and LN_2 during a science experiment.	• Burning sensation in the throat • Severe abdominal pain • Distended abdomen • Shortness of breath • Mild respiratory acidosis • Subcutaneous emphysema • Two small perforations (lesser curvature of stomach)	*(23)*
6	Licenced drinking establishment – *Europe*	Ingestion	Female – *18*	Subject ingested an alcoholic beverage that was prepared with LN_2.	• Severe abdominal pain • Distended abdomen • Shortness of breath • Elevated white cell count: (30.7×10^9/L) • Tachycardia • Large volume pneumoperitoneum • Free intra-abdominal fluid • Erythema (fundus of the stomach) • 4 cm perforation (lesser curvature of stomach) • Necrosis and haemorrhage surrounding perforation site • Damage was so severe, a complete gastrectomy had to be undertaken	*(30)*

Continued on next page

TABLE 1. Peer-reviewed case reports of LN_2 exposure and/or consumption (cont.)

Case #	Setting & Location	Case Type	Sex & Age (Years)	Details of Incident	Clinical Manifestation	Reference
7	N/A – *United Sates*	Ingestion	Male – *19*	Subject knowingly ingested an unknown amount of LN_2 after being dared to do so by friends.	• Abdominal pain • Distended abdomen • Mild respiratory difficulty • White blood cell count: 16,500/ µL • Mild erythema (tongue and oropharynx) • Massive pneumoperitoneum • No perforation	*(39)*
8	N/A – *Asia*	Ingestion	Male – *17*	Subject drank about 30 mL of orange juice mixed with LN_2.	• Severe abdominal pain • Distended abdomen • Slightly elevated white blood cell count • Pneumoperitoneum • Pneumomediastinum • 3 cm perforation (lesser curvature of stomach)	*(41)*
9	Subject's home – *Asia*	Ingestion	Male – *25*	Subject ingested a beverage containing LN_2 prepared at home.	• Abdominal pain • Distended abdomen • Breathing difficulty • Respiratory rate: > 40 breaths/min • Heart rate: > 130 beats/min • O_2 saturation: < 95% • Tachycardia • Severe pneumoperitoneum • Severe pneumomediastinum • Subcutaneous emphysema (facial, neck and back regions) • Bilateral pneumothorax • Bilateral pleural effusion • 6 cm perforation (lesser curvature of stomach)	*(43)*

TABLE 2. Non peer-reviewed case reports of LN_2 exposure and/or consumption

Case #	Setting & Location	Case Type	Sex & Age (Years)	Details of Incident	Clinical Manifestations	Reference
10	Drinking Establishment – *Asia*	Ingestion	Male – *30*	Subject rapidly ingested a cocktail containing LN_2 while it was still emitting smoke.	• Severe pain • Swollen abdomen • Difficulty breathing • Abnormal heart rate, blood pressure and O_2 saturation • Elevated level of lactic acid • Abdominal free air • Large gastric perforation (middle and lower section of the stomach) • Tissue damage near perforation	*(10)*
11	Night Market – *Asia*	Improper handling	Male – *15*	Subject emptied cup containing Dragon's Breath cookies and some residual drops of LN_2 into the palm of his hand.	• Cold burns and blisters (palm of hand) • Swollen palm	*(11)*
12	Local Shop – *Asia*	Ingestion	Female – *N/A*	Subject ate a biscuit coated with LN_2, which then ended up sticking to her gums.	• Cold burns	*(13)*
13	Local Fair – *United States*	Improper handling	Female – *14*	Subject's thumb came into contact with LN_2 while eating her LN_2 infused snack.	• Cold burn on thumb • Tissue necrosis	*(14)*
14	Mall Kiosk – *United States*	Ingestion	Male – *N/A*	Subject ingested cereal puffs coated with LN_2 and blew smoke out his mouth to appear like a dragon.	• Coughing • Trouble breathing • Asthma attack	*(17)*
15	Local Fair – *United States*	Ingestion	Female – *N/A*	Subject followed instructions and ingested LN_2 infused cereal puffs as directed by employee.	• Second-degree burns and blisters (roof of mouth)	*(27)*
16	Water Park – *Asia*	Ingestion	Male – *12*	Subject was suspected to have ingested LN_2 while eating the last few bits of his LN_2 coated cereal puffs.	• 5 cm gastric perforation	*(42)*
17	Fundraiser – *United States*	Ingestion	Female – *N/A*	Subject ingested a cocktail containing LN_2 before it fully evaporated.	• Intense pain • Fluid and gas build up (lungs) • Internal cold burns • Tears or perforations (esophagus, stomach, and bowels)	*(24)*

RISK CHARACTERIZATION

For this review, qualitative risk estimates were made based on the frequency and types of LN_2 injuries reported in the literature from related case reports. These risks are characterized below.

Risk of thermal injury

In terms of direct skin or tissue contact with LN_2, cold burns to the hands or mouth tend to be a commonly encountered injury. The likelihood of cold burns developing is high if direct contact for more than a very brief period of time is made with LN_2 itself, the chilled treats, or the serving cups holding LN_2. The severity of the injury depends on the duration and extent of contact, and the most serious cases may require amputation. However, the likelihood of this occurring is very low because only a few cases have been reported in the literature *(9, 14, 31)*.

Risk of inhalation injury

Generally, when LN_2 is inhaled during consumption, health effects are not likely to occur if exposure is minimal and spaces are well ventilated. However, patrons with asthma or other underlying respiratory conditions may be at risk of experiencing an exacerbation of disease following inhalation of LN_2.

Risk of ingestion injury

Consumers are less likely to be injured if the LN_2 has completely evaporated before they consume the food or beverage containing LN_2 (e.g., ingestion injuries such as gastric perforation would not occur). However, individuals may still experience discomfort or thermal burns due to the cold temperature of the food or beverage *(32)*. On the other hand, if LN_2 itself is ingested prior to its evaporation, there is a risk of developing gastrointestinal barotrauma and perforations. In fact, 10 of the 17 cases reported this as the primary injury experienced after ingestion of LN_2 prior to its evaporation. However, due to potential publication and reporting bias, perforations are more likely to be reported than other types of ingestion injuries. Therefore, these findings should be interpreted carefully.

DISCUSSION

There are many potential injuries that consumers may face when consuming foods and beverages containing LN_2. Among all the ones discussed, inhalation and ingestion injuries tend to be the most severe because they often result in hospitalization or require surgery. Barotrauma with gastric perforation is the most severe outcome identified. Thermal injuries may also occur; however, their health impact tends to be minor because these injuries usually heal after a few days and do not always require hospitalization. Unfortunately, due to the lack of dietary exposure data available on LN_2-infused foods and beverages, it is unknown which age groups are exposed to LN_2 the most. Whereas exposure among certain groups will vary depending on the food or beverage being served (e.g., alcoholic or nonalcoholic), children and young adults may be more likely to try treats that are prepared with LN_2 *(11, 14, 21, 30, 42)*. Based on the case reports reviewed, this age range could be anywhere from 12 to 30 years. However, note that 4 of the 17 case reports reviewed did not mention age, which could lead to an underestimation of risk for the age groups not accounted for. Therefore, this range should be interpreted with caution.

It also appears from the case reports that adverse outcomes related to LN_2 in food may be more frequent in males than females *(2, 30, 41, 43)*. For example, of the 17 cases found in this review, 11 were male and 6 were female. In addition, the most serious outcomes, gastric perforation injuries, were reported in 8 male and 2 female cases. Though the counts are small, it is possible that the higher number of adverse outcomes in males are related to biopsychosocial or environmental factors such as risk-taking behavior and/or peer pressure.

Fortunately, jurisdictions are starting to realize the hazards of LN_2 consumption. For example, although the United States does not prohibit the use of LN_2 in foods, the U.S. Food and Drug Administration did issue a warning in 2018, advising consumers to avoid such treats *(37)*. Moreover, in Canada, Work Safe British Columbia categorized exposure to LN_2 during food preparation as an "emerging risk" to food handlers in 2017 *(3)*. To mitigate such risks, the Ontario Ministry of Labour, Canadian Centre for Occupational Health and Safety, and Work Safe British Columbia published risk advisories and guidelines for how to safely handle the agent in the workplace *(4, 28, 40)*. In the United Kingdom, a bar was fined after a patron's stomach ruptured and had to be removed following ingestion of a LN_2-infused cocktail *(5, 30)*. Despite the risks, LN_2-infused foods and drinks continue to be served around the world. What is more concerning is that there are now online articles and videos explaining to inexperienced viewers how to make these treats at home *(3, 30)*. Thus, to help reduce the risk of injury following consumption of these foods, a list of risk mitigation measures has been provided below for regulatory agencies, vendors, and consumers to consider.

Risk mitigation measures for regulatory agencies

Although such cases are rare, public health authorities should monitor for cases of injury in relation to LN_2 consumption *(30)*. In addition, they should reevaluate its safety whenever new scientific evidence is available *(30)*. To ensure the public is safe from harm, alerts and advisories should be issued when necessary to inform consumers about any potential risks *(30)*. Furthermore, regulators should consider enacting stricter policies with regard to adding LN_2 directly to foods and drinks at points of purchase. For example, rather than mixing food and LN_2 together in

one bowl, a safer alternative would be to use two separate bowls. For instance, one bowl can be used specifically for LN_2, and another smaller bowl can be placed on top with just the food inside. Having LN_2 administered in a separate bowl or compartment from the food can help to prevent the accidental ingestion of LN_2. Ice cream made instantly with LN_2 should be the only exception to this requirement, as long as the LN_2 evaporates before reaching the consumer. Lastly, regulators should only permit the sale of these food products by trained personnel, i.e., those trained on how to properly serve and work with LN_2 *(30)*.

Risk mitigation measures for vendors

Only vendors and employees who are properly trained to handle LN_2 should be allowed to prepare or serve LN_2-infused foods and beverages to the public *(30)*. Only food grade LN_2 stored and served in containers that are specifically manufactured to withstand the thermal effects of LN_2 should be used *(3)*. Such containers should have loose-fitting lids or safety valves to prevent overpressurization and to reduce the risk of explosion *(28)*. To transfer the LN_2, clean flasks specially designed for cryogenic liquids, e.g., a Dewar, should be used *(3)*. When storing, handling, and serving LN_2, proper sanitation and hygiene standards should always be followed to prevent bacterial contamination. In addition, employees should always wear appropriate personal protective equipment when handling LN_2 *(28)*. Establishments should also have working ventilation and oxygen-monitoring systems installed to detect possible leaks or spills *(28)*. Clear instructions should be provided on how to safely handle and ingest these products when serving customers *(3)*. It is also very important that warnings about the potential dangers of LN_2 are posted clearly where consumers can see them *(3)*. Furthermore, utensils and cup sleeves should be provided to consumers to prevent excessive contact with LN_2 *(3)*. Finally, bowls should not be served if they contain any residual LN_2, and consumers should never be permitted to get refills of LN_2 *(3)*.

Risk mitigation measures for consumers

If children want to consume treats prepared with LN_2, an adult should supervise them. As with a hot beverage, patrons should wait a few minutes for their treat to stop steaming or to reach room temperature to avoid thermal injury *(33)*. Before consuming such treats, it is imperative that patrons wait for the LN_2 to completely evaporate, i.e., until no more residual LN_2 is present *(37)*. Additionally, consumers should never touch the residual LN_2 left at the bottom of a serving bowl if present *(33)*. Customers should also blow and fully chew on snacks coated with LN_2 to allow the LN_2 to fully evaporate before ingestion *(33)*. Waiting for the cloudy vapors to subside and eating the snacks one at a time can also help reduce the risk of injury. If any injury or discomfort is experienced following exposure to these treats, consumers should seek medical attention as soon as possible. In summary, although these foods and beverages can be enticing, the best way to avoid injury is to follow these safety precautions or avoid these treats altogether.

CONCLUSION

If the trend of adding LN_2 to foods and beverages immediately before consumption continues to grow, so will exposure. With increased exposure comes an increased risk of injury to the general public. Although LN_2-related injuries appear to be rare, these treats should be handled and consumed with caution because they can potentially result in acute burns, permanent disfiguration, or potentially fatal injuries. Thus, action is needed to inform and educate consumers and vendors about the risks of LN_2-infused foods and beverages. In addition, public health authorities may want to consider developing guidelines and/or policies to help reduce the potential risk from these products. Lastly, as identified in the review, there are still many uncertainties regarding the safety of these treats due to the lack of consumption data and oversight. Therefore, further research in this area would be beneficial to help address issues pertaining to evaporation times in different foods and exposure. In turn, this will help guide regulators to put more relevant and targeted food safety interventions into action.

ACKNOWLEDGMENTS

We express our sincere gratitude to Dr. Kavita Walia for the valuable advice, support, and guidance she graciously offered during this project.

REFERENCES

1. Balasubramanian, S., M. K. Gupta, and K. K. Singh. 2012. Cryogenics and its application with reference to spice grinding: a review. *Crit. Rev. Food Sci. Nutr.* 52:781–794.
2. Berrizbeitia, L. D., D. P. Calello, N. Dhir, C. O'Reilly, and S. Marcus. 2010. Liquid nitrogen ingestion followed by gastric perforation. *Pediatr. Emerg. Care* 26:48–50.
3. British Columbia Centre for Disease Control. 2017. Safety of novel use of liquid nitrogen and dry ice in the food and beverage industry. Available at: http://www.bccdc.ca/resource-gallery/Documents/Educational%20Materials/EH/FPS/Food/Safety_Of_Novel_Use_of_Liquid_Nitrogen_and_Dry_Ice_in_the_Food_and_%20Beverage_Industry.pdf. Accessed 23 March 2019.
4. Canadian Centre for Occupational Health and Safety. 2017. How do I work safely with—cryogenic liquids. Available at: https://www.ccohs.ca/oshanswers/prevention/cryogens.html. Accessed 8 July 2019.
5. Carter, H. 2015. Nitrogen cocktail destroyed birthday woman's stomach. Available at: https://www.bbc.com/news/uk-england-lancashire-34269286. Accessed 26 June 2019.
6. Centers for Disease Control and Prevention. 2018. 2015–2016 National Health and Nutrition Examination Survey. Available at: https://wwwn.cdc.gov/Nchs/Nhanes/2015-2016/DR1IFF_I.htm. Accessed 5 May 2019.
7. Chandra, S., and S. D. Aziz. 1994. Leidenfrost evaporation of liquid nitrogen droplets. *J. Heat Trans.* 116:999–1006.
8. De Solier, I. 2010. Liquid nitrogen pistachios: molecular gastronomy, elBulli and foodies. *Eur. J. Cult. Stud.* 13:155–170.

9. Divya, V. C., and B. Saravanakarthikeyan. 2018. Intraoral frostbite and Leidenfrost effect. *Aust. Dent. J.* 63:382–384.
10. Dutt, A. 2017. Delhi man drinks liquid nitrogen at a bar, ends up with a hole in stomach. Available at: https://www.hindustantimes.com/delhi-news/delhi-man-drinks-liquid-nitrogen-at-a-bar-ends-up-with-a-hole-in-his-stomach/story-Qec1r0Ea84KDk71WIOkhFN.html. Accessed 26 June 2019.
11. Free Malaysia Today. 2016. Teen suffers burns, blisters from Dragon Breath cookies. Available at: https://www.freemalaysiatoday.com/category/nation/2016/12/19/teen-suffers-burns-blisters-from-dragon-breath-cookies/. Accessed 26 June 2019.
12. Gibbs, W., and N. Myhrvold. 2011. Cryogenic cooking. Available at: https://www.scientificamerican.com/article/cryogenic-cooking/. Accessed 23 March 2019.
13. Goh, K. 2017. Dragon's Breath blows into the dessert scene in Singapore. Available at: https://www.straitstimes.com/lifestyle/food/dragons-breath-blows-into-the-dessert-scene-in-singapore. Accessed 26 June 2019.
14. Gonzalez, D. 2017. Liquid nitrogen dessert at fair causing concern for some. Available at: https://weartv.com/news/local/liquid-nitrogen-dessert-at-fair-causing-concern-for-some. Accessed 26 June 2019.
15. Gottfried, B. S., C. J. Lee, and K. J. Bell. 1966. The Leidenfrost phenomenon: film boiling of liquid droplets on a flat plate. *Int. J. Heat Mass Trans.* 9:1167–1188.
16. Government of Canada. 2016. Foodbook report. Available at: https://www.canada.ca/en/public-health/services/publications/food-nutrition/foodbook-report.html. Accessed 5 May 2019.
17. Gutierrez, L. 2018. "It seemed harmless enough." Mom, health officials alarmed about Dragon's Breath snack. Available at: https://www.kansascity.com/news/nation-world/article215966795.html#storylink=cpy. Accessed 26 June 2019.
18. Johnson, C. 2015. Thinking outside the liquid nitrogen freezing box. Available at: http://www.airproducts.com/~/media/downloads/article/C/en-cryogenic-systems-thinking-outside-the-lin-freezing-box.pdf. Accessed 23 March 2019.
19. Kernbach-Wighton, G., H. Kijewski, P. Schwanke, P. Saur, and R. Sprung. 1998. Clinical and morphological aspects of death due to liquid nitrogen. *Int. J. Legal Med.* 111:191–195.
20. Kim, D. H., and H. J. Lee. 2008. Evaporated liquid nitrogen-induced asphyxia: a case report. *J. Korean Med. Sci.* 23:163–165.
21. Kim, D. W. 2018. Stomach perforation caused by ingesting liquid nitrogen: a case report on the effect of a dangerous snack. *Clin. Endosc.* 51:381–383.
22. Knudsen, A. R., C. Nielsen, and P. Christensen. 2009. Gastric rupture after ingestion of liquid nitrogen. *Ugeskr. Laeger* 171:534–534.
23. Koplewitz, B. Z., A. Daneman, S. H. Ein, M. A. McGuigan, and M. Mian. 2000. Gastric perforation attributable to liquid nitrogen ingestion. *Pediatrics* 105:121–123.
24. Local 10 News. 2014. Woman served "toxic cocktail" at Miami Beach fundraiser. Available at: https://www.local10.com/news/woman-served-toxic-cocktail-at-miami-beach-fundraiser. Accessed 29 June 2019.
25. Morales, I., J. Keshavamurthy, N. Patel, and N. Thomson. 2017. Inert gas asphyxiation: a liquid nitrogen accident. *Chest* 152:A378.
26. National Center for Biotechnology Information. 2004. Nitrogen. PubChem database. Available at: https://pubchem.ncbi.nlm.nih.gov/compound/Nitrogen. Accessed 12 April 2019.
27. Newby, J. 2017. Fair general manager: controversial "Dragon's Breath" concession won't be back next year. Available at: https://www.pnj.com/story/news/local/2017/10/27/fair-general-manager-controversial-dragons-breath-concession-wont-back-next-year/803757001/. Accessed 26 June 2019.
28. Ontario Ministry of Labour. 2016. Liquid nitrogen in the food and beverage industry. Available at: https://www.labour.gov.on.ca/english/hs/pubs/ib_liquidnitrogen.php. Accessed 8 July 2019.
29. Pessoa, G. A., M. I. B. Rubin, C. A. M. Silva, and D. C. D. Rosa. 2014. Decontamination of naturally contaminated liquid nitrogen storage tanks. *Rev. Bras. Zootec.* 43:244–249.
30. Pollard, J. S., J. E. Simpson, and M. I. Bukhari. 2013. A lethal cocktail: gastric perforation following liquid nitrogen ingestion. *BMJ Case Rep.* 2013:bcr2012007769.
31. Roblin, P., A. Richards, and R. Cole. 1997. Liquid nitrogen injury: a case report. *Burns* 23:638–640.
32. Rockswold, G., and D. J. Buran. 1982. Inhalation of liquid nitrogen vapor. *Ann. Emerg. Med.* 11:553–555.
33. Roustan, K. W. 2018. Dragon's Breath liquid nitrogen snacks may be too hot to handle, mother warns. Available at: https://www.bramptonguardian.com/living-story/8799272-dragon-s-breath-liquid-nitrogen-snacks-may-be-too-hot-to-handle-mother-warns/. Accessed 26 June 2019.
34. Tassou, S. A., J. S. Lewis, Y. T. Ge, A. Hadawey, and I. Chaer. 2010. A review of emerging technologies for food refrigeration applications. *Appl. Therm. Eng.* 30:263–276.
35. Tedder, R., M. A. Zuckerman, N. S. Brink, A. H. Goldstone, A. B. E. M. Fielding, S. Blair, K. G. Patterson, A. E. Hawkins, A. M. Gormon, J. Heptonstall, and D. Irwin. 1995. Hepatitis B transmission from contaminated cryopreservation tank. *Lancet* 346:137–140.
36. U.S. Food and Drug Administration. 2018. FDA advises consumers to avoid eating, drinking, or handling food products prepared with liquid nitrogen at the point of sale. Available at: https://www.fda.gov/Food/RecallsOutbreaksEmergencies/SafetyAlertsAdvisories/ucm618058.htm. Accessed 23 March 2019.
37. U.S. Food and Drug Administration. 2018. Liquid nitrogen and dry ice in food. Available at: https://www.fda.gov/media/117281/download. Accessed 8 July 2019.
38. Ventura, G., and L. Risegari. 2010. The art of cryogenics: low-temperature experimental techniques, 1st ed. Elsevier Ltd., Oxford.
39. Walsh, M. J., S. R. Tharratt, and S. R. Offerman. 2010. Liquid nitrogen ingestion leading to massive pneumoperitoneum without identifiable gastrointestinal perforation. *J. Emerg. Med.* 38:607–609.
40. Work Safe British Columbia. 2017. Risk advisory: liquid nitrogen exposure in food preparation. Available at: https://www.worksafebc.com/en/resources/health-safety/risk-advisory/liquid-nitrogen-exposure-in-food-preparation?lang=en&direct. Accessed 8 July 2019.
41. Yaegashi, Y., F. Nakajima, N. Hosoi, H. Fukuta, and M. Sase. 2000. Case of gastrorrhexis caused by ingestion liquid nitrogen. *Jpn. J. Gastroenterol. Surg.* 33:1648–1651.
42. Yonhap News Agency. 2017. Liquid nitrogen treat forms hole in boy's stomach Available at: https://en.yna.co.kr/view/AEN20170803011000315. Accessed 26 June 2019.
43. Zheng, Y., X. Yang, and X. Ni. 2018. Barotrauma after liquid nitrogen ingestion: a case report and literature review. *J. Postgrad. Med.* 130:511–514.

APPENDIX

Appendix A. Search strategy used to obtain scholarly literature

Database	Search no.	Searches	No. of records retrieved
Ovid MEDLINE	1	Liquid nitrogen.m_titl.	1,131
	2	drink*.ti,ab.	166,416
	3	beverage*.ti,ab	29,904
	4	Cocktail*.ti,ab.	12,792
	5	2 or 3 or 4	200,404
	6	1 and 5	4
	7	Ingestion*.ti,ab.	83,008
	8	Consumption*.ti,ab.	336,607
	9	Inhalation*,ti,ab.	75,211
	10	7 or 8 or 9	483,165
	11	1 and 10	15
	12	Ice cream*.ti,ab.	1,557
	13	Snack.mp*.ti,ab.	8,856
	14	12 or 13	10,313
	15	1 and 14	1
	16	Injury*.ti,ab	826,458
	17	Risk*.ti,ab.	2,802,356
	18	Danger*.ti,ab.	75,029
	19	Effect*.ti,ab.	8,089,620
	20	16 or 17 or 18 or 19	10,564,240
	21	1 and 10 and 20	9
	22	Barotrauma*.ti,ab.	3,090
	23	Gastric perforation*.ti,ab.	1,429
	24	Airway perforation*.ti,ab.	2
	25	Pneumoperitoneum*.ti,ab.	8,922
	26	22 or 23 or 24 or 25	13,286
	27	1 and 26	10
	28	Asphyxiation*.ti,ab.	1,287
	29	1 and 28	2
	30	Death*.ti,ab.	995,469
	31	1 and 30	11
Google Scholar	32	Gastrorrhexis and liquid nitrogen	15
Web of Science	33	Liquid nitrogen and frostbite	21
TOXNET	34	Liquid nitrogen	4,204

Appendix B. Websites and databases used to obtain gray literature

Source	Title
	Liquid Nitrogen in the Food and Beverage Industry
Ontario Ministry of Labour U.S. Food and Drug Administration	a) FDA Advises Consumers to Avoid Eating, Drinking, or Handling Food Products Prepared with Liquid Nitrogen at the Point of Sale
	b) Liquid nitrogen and dry ice in food
British Columbia Centre for Disease and Control	Safety of novel use of liquid nitrogen and dry ice in the food and beverage industry
Work Safe British Columbia	Risk Advisory: Liquid nitrogen exposure in food preparation
Government of Canada	Foodbook Report
Canadian Centre for Occupational Health and Safety	How do I work safely with – cryogenic
Centers for Disease Control and Prevention	National Health and Nutrition Examination Survey
National Center for Biotechnology Information	Nitrogen
Local 10	Woman served "toxic cocktail" at Miami Beach fundraiser
Free Malaysia Today	Teen suffers burns, blisters from Dragon Breath cookies
The Standard	Dragon's Breath liquid nitrogen snacks may be too hot to handle, mother warns
Pensacola News Journal	Fair general manager: Controversial "Dragon's Breath" concession won't be back next year
Yonhap News Agency	Liquid nitrogen treat forms hole in boy's stomach
Kansas City Star	"It seemed harmless enough." Mom, health officials alarmed about Dragon's Breath snack
ABC WEAR-TV	Liquid nitrogen dessert at fair causing concern for some
The Straights Times	Dragon's Breath blows into the dessert scene in Singapore
Scientific American	Cryogenic cooking
Hindustan Times	Delhi man drinks liquid nitrogen at a bar, ends up with a hole in stomach
Air Products	Thinking outside the liquid nitrogen freezing box