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Foodborne pathogens in raw milk: A review of risks and control measures

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Abstract

This review examines the presence and significance of foodborne pathogens in raw milk, the associated public health risks, and the effectiveness of various control measures. Despite growing consumer interest in raw milk consumption due to perceived nutritional benefits, it remains a significant vehicle for foodborne pathogen transmission. Major pathogens of concern include *Listeria monocytogenes*, *Campylobacter* species, *Salmonella* species, pathogenic *Escherichia coli*, *Brucella* species, *Mycobacterium bovis*, and *Coxiella burnetii*. This review discusses the contamination sources, prevalence, and characteristics of these pathogens, along with the epidemiology of raw milk-associated outbreaks. Additionally, it evaluates traditional and emerging control strategies, including good agricultural practices, testing programs, improved cold chain management, high-pressure processing, and consumer education. The review synthesizes current literature to provide recommendations for mitigating health risks while addressing consumer concerns in evolving regulatory frameworks.

Keywords: Raw milk, foodborne pathogens, food safety, zoonotic diseases, pasteurization alternatives, risk assessment

1. Introduction

Despite significant public health concerns, Raw milk consumption has grown in popularity in many countries (Costard *et al.*, 2017) ^[8]. Advocates of raw milk consumption claim various nutritional advantages, including enhanced nutrient bioavailability, beneficial enzymes, and potential protective effects against allergies and asthma (Brick *et al.*, 2020) ^[3]. However, these purported benefits remain controversial within the scientific community, and many health organizations, including the World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC), continue to warn about the significant risks associated with raw milk consumption (WHO, 2018; CDC, 2022) ^[56].

Raw milk, defined as milk that has not undergone pasteurization or other equivalent treatment to reduce microbial load, can harbor various pathogenic microorganisms (Oliver *et al.*, 2009) ^[42]. These pathogens can originate from the dairy animal, the farm environment, or the equipment used during milk collection and handling (Quigley *et al.*, 2013) ^[46]. These pathogens pose substantial public health risks, particularly for vulnerable populations such as pregnant women, children, the elderly, and immunocompromised individuals (Mungai *et al.*, 2015) ^[37].

The regulatory landscape surrounding raw milk production and sales varies significantly across countries and even within regions of the same country. While some jurisdictions prohibit the sale of raw milk entirely, others permit it through various regulated channels, including direct farm-to-consumer sales, herdshare programs, or as pet food (Whitehead & Lake, 2018) ^[55]. This regulatory inconsistency reflects the ongoing tension between consumer choice and public health protection.

This review aims to comprehensively examine the microbiological risks associated with raw milk consumption, focusing on major foodborne pathogens, their sources, prevalence, and characteristics. It also discusses the epidemiology of outbreaks linked to raw milk consumption and evaluates traditional and emerging control strategies to mitigate these risks. Finally, it provides recommendations for stakeholders involved in raw milk production, regulation, and consumption in light of the current scientific evidence.

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2. Major Foodborne Pathogens in Raw Milk

2.1 *Listeria monocytogenes*

Listeria monocytogenes represents one of raw milk's most significant bacterial hazards due to its ubiquitous presence in the farm environment and ability to grow at refrigeration temperatures (Farber & Peterkin, 2018) [17]. This gram-positive bacterium causes listeriosis, a potentially fatal foodborne illness with a mortality rate of approximately 20-30% among clinical cases (European Food Safety Authority [EFSA], 2023).

The prevalence of *L. monocytogenes* in raw milk samples varies considerably among studies, ranging from 1% to 12% (Hunt *et al.*, 2018; Jamali *et al.*, 2013) [25, 27]. A meta-analysis by Martinez-Rios and Dalgaard (2018) [34] estimated an average prevalence of 2.5% (95% CI: 1.8-3.4%) in raw cow's milk in developed countries. The primary sources of *L. monocytogenes* contamination include poor silage quality, inadequate hygiene during milking, mastitis in dairy animals, and biofilm formation on milking equipment (Fox *et al.*, 2011) [19].

L. monocytogenes possesses several characteristics that enhance its potential as a foodborne pathogen in raw milk. Its psychrotrophic nature allows growth at temperatures as low as -0.4°C, meaning that refrigeration alone cannot prevent its proliferation (Buchanan *et al.*, 2017) [4]. Additionally, the bacterium can form biofilms on various surfaces, providing resistance against cleaning procedures and sanitizing agents (Rodríguez-López *et al.*, 2018) [51].

2.2 *Campylobacter* species

Campylobacter species, particularly *C. jejuni* and *C. coli*, are leading causes of bacterial gastroenteritis worldwide and are frequently associated with raw milk consumption (Kaakoush *et al.*, 2015) [28]. These gram-negative, microaerophilic bacteria cause campylobacteriosis, characterized by diarrhea, abdominal pain, and fever, with potential long-term sequelae including Guillain-Barré syndrome (GBS) and reactive arthritis (Nachamkin *et al.*, 2008) [39].

The prevalence of *Campylobacter* in raw milk varies widely, with studies reporting ranges from 0% to 27% (Stanley *et al.*, 2021; Bianchini *et al.*, 2014) [52, 2]. A systematic review by Christidis *et al.* (2020) [7] calculated a pooled prevalence estimate of 4.5% (95% CI: 2.8-6.9%) in raw cow's milk. Fecal contamination during milking represents the primary source of *Campylobacter* in raw milk, as these organisms naturally colonize the intestinal tract of many dairy animals without causing disease (Rapp & Ross, 2012) [48].

Unlike *L. monocytogenes*, *Campylobacter* species do not multiply in foods stored at refrigeration temperatures. However, they possess a remarkably low infectious dose, with as few as 500 organisms capable of causing disease (Robinson, 2019) [49]. This characteristic makes raw milk particularly hazardous even when contaminated with relatively low numbers of *Campylobacter* cells.

2.3 *Salmonella* species

Salmonella are gram-negative, facultatively anaerobic bacteria responsible for salmonellosis, a disease characterized by gastroenteritis and systemic infection in severe cases (Crump *et al.*, 2022) [9]. Raw milk has been implicated in numerous salmonellosis outbreaks, with *S. Typhimurium* and *S. Dublin* being the most frequently reported serotypes in dairy-related cases (Zeleny *et al.*, 2021) [57].

Studies investigating the prevalence of *Salmonella* in raw milk report detection rates ranging from 0.2% to 8.9%

(Jackson *et al.*, 2012; Karshima *et al.*, 2013) [26, 30]. A comprehensive review by Parisi *et al.* (2019) [44] estimated an average prevalence of 1.5% (95% CI: 0.9-2.3%) in raw cow's milk worldwide. Environmental contamination, subclinical mastitis, and poor hygiene practices during milking are the primary sources of *Salmonella* in raw milk (McLauchlin & Aird, 2019) [35].

Salmonella Dublin deserves special mention due to its adaptation to cattle and its association with invasive disease in humans who consume contaminated raw milk (Holschbach & Peek, 2018) [24]. Studies have shown that *S. Dublin* can persist in dairy herds for extended periods, posing an ongoing risk for raw milk contamination (Nielsen, 2013) [40].

2.4 Shiga toxin-producing *Escherichia coli* (STEC)

Shiga toxin-producing *Escherichia coli* (STEC), particularly serotype O157

Moreover, other non-O157 STEC represent significant hazards in raw milk (Majowicz *et al.*, 2014) [32]. STEC infections can cause severe bloody diarrhea and potentially life-threatening complications, including hemolytic uremic syndrome (HUS), which primarily affects children under five years of age (Tarr *et al.*, 2005) [53].

According to various studies, the prevalence of STEC in raw milk ranges from 0% to 5.7% (Murphy *et al.*, 2016; Elhadidy & Mohammed, 2013) [38, 13]. Farrokh *et al.*'s (2013) [18] meta-analysis reported a pooled prevalence estimate of 0.9% (95% CI: 0.5-1.5%) for STEC in raw cow's milk. Cattle serve as the primary reservoir for STEC, with fecal contamination during milking being the most common route of raw milk contamination (Persad & LeJeune, 2014) [45].

Like *Campylobacter*, STEC possesses a very low infectious dose, with fewer than 100 organisms capable of causing disease (Teunis *et al.*, 2004) [54]. This characteristic, combined with the severity of STEC-related illnesses, makes these pathogens particularly concerning in raw milk.

2.5 *Brucella* species

Brucella species are gram-negative, facultatively intracellular pathogens responsible for brucellosis, a zoonotic disease characterized by undulant fever, arthritis, and potentially serious complications affecting various organ systems (Pappas *et al.*, 2006) [43]. *B. abortus* (from cattle) and *B. melitensis* (from goats and sheep) are the species most commonly associated with raw milk transmission (Gupta *et al.*, 2014) [22].

The prevalence of *Brucella* in raw milk varies considerably depending on the geographic region and the brucellosis control programs in place. In endemic areas, studies have reported prevalence rates ranging from 1.5% to 17% in raw milk samples (Gwida *et al.*, 2012; Kang'ethe *et al.*, 2007) [23, 29]. In contrast, countries with effective eradication programs report negligible detection rates (Centers for Disease Control and Prevention, 2017) [5].

Brucella organisms can be directly excreted in the milk of infected animals, making raw milk from infected herds a significant transmission vehicle (Pappas *et al.*, 2006) [43]. The bacteria can survive in refrigerated dairy products for extended periods, increasing the risk associated with raw milk consumption (Estrada *et al.*, 2005) [15].

2.6 *Mycobacterium bovis*

Mycobacterium bovis, the causative agent of bovine tuberculosis, can be transmitted to humans by consuming raw milk from infected cattle (Olea-Popelka *et al.*, 2017) [41].

Human infection with *M. bovis* results in a disease clinically indistinguishable from that caused by *M. tuberculosis*, potentially affecting any organ system but with a predilection for extrapulmonary manifestations (de la Rua-Domenech, 2006)^[10].

The prevalence of *M. bovis* in raw milk is difficult to ascertain due to the challenging nature of its isolation and identification. Studies using molecular methods have reported detection rates ranging from 0% to 33% in raw milk from regions where bovine tuberculosis is endemic (Kazwala *et al.*, 1998; Ayele *et al.*, 2004)^[31, 1]. In countries with effective bovine tuberculosis control programs, the risk of *M. bovis* in raw milk is significantly reduced but not eliminated (Marcotty *et al.*, 2013)^[33].

M. bovis can be directly excreted in the milk of infected cows, particularly those with tuberculous mastitis. The organism's ability to survive for extended periods in refrigerated milk increases the risk associated with raw milk consumption (Michel *et al.*, 2015)^[36].

2.7 *Coxiella burnetii*

Coxiella burnetii is an obligate intracellular bacterium and the causative agent of Q fever, a zoonotic disease that can manifest as an acute febrile illness or develop into a chronic infection. It primarily affects the heart (endocarditis) or, less commonly, the liver or brain (Eldin *et al.*, 2017)^[12]. Although airborne transmission represents the primary route for human infection, consuming contaminated raw milk may also serve as a transmission pathway (Gale *et al.*, 2015)^[20].

Studies investigating the prevalence of *C. burnetii* in raw milk have reported detection rates ranging from 0% to 94%, depending on the geographic region and detection method employed (Eldin *et al.*, 2013; Rahimi *et al.*, 2011)^[11, 47]. PCR-based studies generally report higher prevalence rates than culture-based methods due to the challenging nature of *C. burnetii* isolation (Guatteo *et al.*, 2007)^[21].

Infected dairy animals, particularly those experiencing abortion due to *C. burnetii* infection, can shed large numbers of the organism in their milk (Rodolakis *et al.*, 2007)^[50]. The extraordinary environmental stability of *C. burnetii*, attributed to its spore-like form, allows it to survive various environmental stressors, including pasteurization at specific time and temperature combinations (Enright *et al.*, 1957)^[14].

3. Epidemiology of Raw Milk-Associated Outbreaks

3.1 Global Burden and Trends

Raw milk consumption continues to be associated with foodborne disease outbreaks globally. An analysis of raw milk-associated outbreaks from 1993 to 2012 in the United States identified 127 outbreaks resulting in 1,909 illnesses, 144 hospitalizations, and two deaths (Mungai *et al.*, 2015)^[37]. More recent data from the CDC indicate that the rate of raw milk-associated outbreaks has not decreased despite enhanced awareness of associated risks (CDC, 2022).

In the European Union, the European Food Safety Authority (EFSA) reported 27 outbreaks linked to consuming raw milk and products between 2007 and 2017, affecting 641 individuals (EFSA, 2018). However, this figure likely underestimates the burden due to significant underreporting in many countries.

The epidemiological picture in developing nations is less clear due to limited surveillance systems and diagnostic capabilities. Nevertheless, studies from various regions suggest that raw milk consumption contributes significantly to the burden of foodborne diseases, particularly brucellosis and

tuberculosis, in areas where these diseases remain endemic in livestock populations (Grace, 2015).

3.2 Case Studies of Significant Outbreaks

Several notable outbreaks highlight the persistent public health risks associated with raw milk consumption:

1. **Pennsylvania, 2017:** A multistate outbreak of *Listeria monocytogenes* infections linked to raw milk from a single dairy farm resulted in 2 deaths and eight hospitalizations across four states (CDC, 2017). The investigation identified identical strains of *L. monocytogenes* in the milk, the farm environment, and clinical isolates from affected individuals.
2. **Tennessee, 2018:** An outbreak of *E. coli* O157 Infections associated with a cow-share program affected 15 people, including nine children. Four children developed hemolytic uremic syndrome (HUS), requiring intensive medical care (Crowe *et al.*, 2019).
3. **France, 2018-2019:** Consumption of raw milk cheeses led to an outbreak of *Salmonella* Dublin infections affecting 83 people, resulting in 41 hospitalizations and 10 deaths. The high mortality rate highlighted the particular virulence of *S. Dublin* and its propensity to cause invasive disease (Jones *et al.*, 2019).
4. **United Kingdom, 2019:** A cluster of campylobacteriosis cases linked to raw milk from a farm offering direct sales affected 69 individuals. The outbreak strain was isolated from patients and the farm's milk tank, with identical genetic profiles confirmed through whole-genome sequencing (Wilson *et al.*, 2020).

3.3 Factors Influencing Outbreak Occurrence

Several factors influence the occurrence and scale of raw milk-associated outbreaks:

1. **Regulatory Framework:** Jurisdictions with permissive raw milk regulations typically report higher incidences of associated outbreaks. Mungai *et al.* (2015)^[37] noted that the rate of reported outbreaks was 2.2 times higher in U.S. states allowing the legal sale of raw milk compared to states prohibiting such sales.
2. **Herd Size and Management Practices:** Larger herd sizes can increase the risk of pathogen presence, while intensive production systems may create favorable pathogen transmission among animals (Costard *et al.*, 2017)^[8].
3. **Seasonal Variations:** Several studies have identified seasonal patterns in raw milk-associated outbreaks, with higher incidences during warmer months. This pattern may reflect increased pathogen loads in the farm environment, challenges maintaining cold chain integrity, or seasonal variations in consumption patterns (Davis *et al.*, 2016).
4. **Consumer Demographics:** Outbreaks often disproportionately affect children and adolescents, reflecting their higher vulnerability to specific pathogens and consumption patterns within households purchasing raw milk (Robinson *et al.*, 2014)^[49].

4. Control Measures and Risk Mitigation Strategies

4.1 On-Farm Preventive Measures

Implementing robust on-farm practices represents the first line of defense against pathogen contamination of raw milk:

1. **Herd Health Management:** Regular veterinary supervision, vaccination programs, and prompt isolation of sick animals can significantly reduce the risk of

pathogen shedding into milk (Ruegg, 2017). Particular attention should be paid to mastitis prevention and control, as subclinical mastitis can lead to increased pathogen loads in milk without obvious clinical signs in the animal (Gruet *et al.*, 2001).

2. **Hygienic Milking Practices:** Proper pre-milking teat preparation, including cleaning and disinfection, can reduce the microbial load transferred to milk during the milking process (Gleeson *et al.*, 2013). Additionally, training milking personnel in hygiene practices and providing appropriate facilities for hand washing and equipment sanitization are essential components of a comprehensive prevention strategy (Visser & Driehuis, 2009).
3. **Environmental Management:** Maintaining clean housing areas, implementing effective waste management systems, and controlling pest populations can minimize environmental reservoirs of pathogens that might contaminate milk (Barkema *et al.*, 2015). Particular attention should be paid to the quality of bedding materials and the cleanliness of water sources, as these represent significant potential sources of contamination (Hauge *et al.*, 2012).
4. **Feed Quality Control:** Ensuring the quality of animal feed, particularly silage, can reduce the environmental burden of specific pathogens, notably *L. monocytogenes* (Sanaa *et al.*, 1993). This control strategy's regular testing of feed materials and proper storage conditions are essential components.

4.2 Testing Programs and Microbiological Criteria

Implementing regular testing protocols for raw milk can help identify contamination issues and verify the effectiveness of preventive measures:

1. **Indicator Organism Testing:** Monitoring the levels of indicator organisms, such as aerobic plate count, coliforms, and *E. coli*, can provide information about overall hygiene conditions (Murphy *et al.*, 2016) [38]. However, it is important to note that the absence of indicator organisms does not guarantee the absence of pathogens, as numerous studies show poor correlation between indicator levels and pathogen presence (Hill *et al.*, 2012).
2. **Pathogen-Specific Testing:** Direct testing for specific pathogens provides more definitive information about safety risks but presents challenges related to sensitivity, specificity, cost, and time-to-result (Ganesan *et al.*, 2012). Recent advances in molecular methods, particularly real-time PCR and whole genome sequencing, have improved the feasibility of routine pathogen testing in raw milk (Quigley *et al.*, 2013) [46].
3. **Sampling Strategies:** The effectiveness of testing programs depends significantly on the sampling strategy employed. Sampling frequency, sample volume, and the specific sampling points within the production system all influence the likelihood of detecting contamination when present (Lombard *et al.*, 2020). Statistical approaches to sampling design can help optimize detection capability within practical constraints (Meyer-Broseta *et al.*, 2003).
4. **Interpretation and Action Limits:** Establishing clear criteria for interpreting test results and defining appropriate corrective actions is essential for the effectiveness of testing programs (European Commission, 2005). These criteria should be based on scientific evidence regarding the relationship between

test results and public health risk while considering practical feasibility for producers.

4.3 Cold Chain Management

Maintaining appropriate temperature control throughout the production, distribution, and storage of raw milk is critical for limiting pathogen growth:

1. **Rapid Cooling:** Prompt milk cooling after collection can significantly inhibit the growth of mesophilic pathogens. Industry guidelines typically recommend cooling milk to 4°C or below within 2 hours of milking (Ruegg, 2003). Implementing pre-cooling systems and efficient bulk tank refrigeration can facilitate achieving this target (O'Connell *et al.*, 2016).
2. **Temperature Monitoring:** Continuous temperature monitoring throughout the cold chain using automated systems with alert capabilities can help identify deviations that might compromise safety (Murphy *et al.*, 2016) [38]. Data logging temperature monitors that provide time-temperature history offer advantages over point-in-time measurements for evaluating cold chain integrity (James *et al.*, 2017).
3. **Distribution Challenges:** Maintaining temperature control during distribution presents particular challenges, especially for direct-to-consumer sales and farmers' markets. Insulated containers, ice packs, and consumer education regarding proper handling can help mitigate these challenges (Giacometti *et al.*, 2012).
4. **Consumer Storage Practices:** Proper storage at the consumer level represents the final critical point in the cold chain. Studies indicate that consumer refrigerators frequently operate above recommended temperatures, potentially allowing the growth of psychrotrophic pathogens like *L. monocytogenes* (Evans & Redmond, 2016). Therefore, consumer education regarding proper storage temperature and shelf-life limitations is essential.

4.4 Non-Thermal Processing Technologies

Various non-thermal processing technologies have been investigated as potential alternatives to thermal pasteurization for enhancing the safety of raw milk while preserving its organoleptic and nutritional characteristics:

1. **High-Pressure Processing (HPP):** Application of high hydrostatic pressure (typically 400-600 MPa) can inactivate vegetative bacterial cells while minimizing changes to the sensory and nutritional properties of milk (Chawla *et al.*, 2011). Studies have demonstrated 3-5 log reductions in pathogens including *L. monocytogenes*, *Salmonella*, and *E. coli* O157. Through HPP treatment (Huppertz *et al.*, 2018). However, spore-forming bacteria and some viruses exhibit significant pressure resistance, potentially limiting the technology's effectiveness as a complete pasteurization alternative (Black *et al.*, 2007).
2. **Pulsed Electric Fields (PEF):** This technology involves applying short pulses of high electric field strength (typically 15-40 kV/cm) to inactivate microorganisms through electroporation of cell membranes (Buckow *et al.*, 2014). PEF has shown promise for reducing bacterial loads in milk with minimal thermal effects, achieving 3-4 log reductions in various pathogens (Sobrinho-López & Martín-Belloso, 2010). However, limitations include effectiveness against spore-formers, equipment cost, and energy requirements.
3. **Ultraviolet (UV) Light:** UV-C irradiation (wavelength

254 nm) has demonstrated effectiveness against various milk-borne pathogens, particularly when combined with turbulent flow systems to overcome the limited penetration depth in opaque liquids like milk (Alberini *et al.*, 2015). Recent advances in UV-LED technology and reactor design have improved the feasibility of UV treatment for milk (Crook *et al.*, 2015). However, challenges remain regarding complete inactivation of all relevant pathogens and potential photochemical changes to milk components.

4. **Ultrasound:** High-power ultrasound can inactivate microorganisms through cavitation effects, generating localized high temperatures and pressures and free radical formation (Bermúdez-Aguirre *et al.*, 2011). When combined with mild heat (thermosensation), ultrasound treatment has achieved significant reductions in pathogen levels in milk (Herceg *et al.*, 2012). However, current applications face limitations related to scalability, energy efficiency, and potential effects on milk fat structure.

4.5 Consumer Education and Risk Communication

Effective communication of risks and appropriate handling practices represents an essential component of a comprehensive approach to raw milk safety:

1. **Evidence-Based Communication:** Information provided to consumers should accurately reflect the current scientific understanding of risks and benefits associated with raw milk consumption (Young *et al.*, 2019). This includes acknowledging areas of scientific uncertainty while emphasizing well-established risks, particularly for vulnerable populations.
2. **Targeted Messages:** Communication strategies should be tailored to address raw milk consumers' specific concerns and motivations (Perkiömäki *et al.*, 2012). Research indicates that raw milk consumers are often motivated by perceived health benefits, support for local agriculture, and skepticism regarding industrial food processing (Katafiasz & Bartlett, 2012). Addressing these motivations while acknowledging legitimate concerns can enhance the effectiveness of risk communication.
3. **Handling Instructions:** Clear guidance regarding proper handling, storage, and consumption practices can help consumers minimize risks associated with raw milk (Langer *et al.*, 2012). This includes recommendations regarding refrigeration temperature, storage duration, and the importance of avoiding consumption by high-risk individuals.
4. **Transparency:** Providing consumers access to relevant information, including test results and outbreak data, can build trust and enable informed decision-making (Wilson *et al.*, 2014). Some successful raw milk safety programs have incorporated transparent sharing of microbiological test results as a core component (Baars *et al.*, 2019).

5. Regulatory Approaches and Policy Considerations

5.1 Current Regulatory Landscape

The regulatory approach to raw milk varies significantly among countries and even within regions of individual countries:

1. **Prohibition:** Some jurisdictions, including Scotland and most Australian states, entirely prohibit the sale of raw milk for human consumption (Whitehead & Lake, 2018)^[55]. These approaches prioritize public health protection based on the well-documented risks associated with raw milk consumption.

2. **Restricted Access:** Other jurisdictions permit raw milk sales through specific, regulated channels. For example, numerous U.S. states allow farm-direct or cow-share programs while prohibiting retail sales (National Conference of State Legislatures, 2020). Similarly, England and Wales permit direct farm sales with specific labeling and hygiene requirements (Food Standards Agency, 2017).
3. **Regulated Retail Sales:** A smaller number of jurisdictions, including certain European countries (e.g., France, Italy) and several U.S. states (e.g., California, Connecticut), permit retail sales of raw milk subject to specific licensing, testing, and labeling requirements (Whitehead & Lake, 2018; National Conference of State Legislatures, 2020)^[55].
4. **Risk-Based Approaches:** Some jurisdictions have implemented risk-based regulatory frameworks that adjust requirements based on the intended use of raw milk, the scale of production, or the target consumer population (European Commission, 2004). Such approaches aim to allocate regulatory resources efficiently while providing proportionate oversight based on the level of risk.

5.2 Balancing Consumer Choice and Public Health Protection

The regulatory challenge surrounding raw milk fundamentally involves balancing respect for consumer autonomy with the governmental responsibility to protect public health:

1. **Informed Choice:** Proponents of raw milk access argue that informed consumers should have the right to choose raw milk despite known risks, similar to other risky but legal consumer products like alcohol and tobacco (Katafiasz & Bartlett, 2012). This perspective emphasizes the importance of accurate information and transparent labeling rather than prohibition.
2. **Vulnerability Considerations:** Critical perspectives on raw milk access often highlight that consumption decisions may affect vulnerable individuals, including children, who may not have made an informed choice (Costard *et al.*, 2017)^[8]. This concern is particularly relevant given that children represent a disproportionate share of severe illnesses in raw milk outbreaks (Robinson *et al.*, 2014)^[49].
3. **Economic Impact:** Regulatory approaches can significantly impact small-scale dairy producers, for whom direct marketing of raw milk may represent an important economic opportunity (Baars *et al.*, 2019). Finding regulatory models that protect public health while allowing economic viability for diverse production scales remains challenging.
4. **Scientific Uncertainty:** The ongoing scientific debate regarding potential benefits of raw milk consumption, particularly about asthma and allergy outcomes, complicates the regulatory calculus (Brick *et al.*, 2020)^[3]. As scientific understanding evolves, regulatory frameworks may need to adapt accordingly.

5.3 Emerging Models and Best Practices

Several innovative regulatory approaches have emerged that attempt to address the complexities of raw milk safety:

1. **Tiered Systems:** Some jurisdictions have implemented tiered licensing systems with requirements that scale with production volume and distribution reach (Whitehead & Lake, 2018)^[55]. Such systems aim to provide appropriate

oversight while avoiding disproportionate burdens on small producers.

2. **Risk-Based Testing:** Advanced approaches to microbiological testing incorporate risk factors such as previous test results, seasonal variations, and farm-specific characteristics to optimize testing frequency and focus (Meyer-Broseta *et al.*, 2003). These approaches aim to maximize safety assurance while minimizing unnecessary testing costs.
3. **Performance Standards:** Outcome-based regulatory approaches that specify required safety performance (e.g., maximum allowable pathogen prevalence) while allowing flexibility in the means of achievement have shown promise in some contexts (Baars *et al.*, 2019). Such approaches can encourage innovation while maintaining focus on public health outcomes.
4. **Farm Safety Plans:** Comprehensive, documented safety plans similar to HACCP (Hazard Analysis Critical Control Point) systems but adapted to the farm context have been implemented in some jurisdictions (Ruegg, 2017). These plans require producers to identify potential hazards and implement appropriate preventive measures specific to their operation.

6. Conclusion and Future Directions

6.1 Summary of Key Findings

This review has examined the current state of knowledge regarding foodborne pathogens in raw milk, highlighting several key points:

1. Raw milk can harbor diverse pathogenic microorganisms, including bacteria (*L. monocytogenes*, *Campylobacter* spp., *Salmonella* spp., STEC, *Brucella* spp., *M. bovis*, *C. burnetii*), viruses, and parasites, posing significant public health risks.
2. The epidemiological evidence consistently demonstrates an association between raw milk consumption and foodborne disease outbreaks, with particularly severe outcomes often observed in vulnerable populations such as children and the elderly.
3. Multiple control strategies, including on-farm preventive measures, testing programs, cold chain management, and emerging non-thermal processing technologies, can reduce but not eliminate pathogen risks in raw milk.
4. Consumer education and risk communication represent essential components of a comprehensive approach to raw milk safety, particularly in contexts where legal access is permitted.
5. Regulatory approaches vary widely across jurisdictions, reflecting different perspectives on the appropriate balance between consumer choice and public health protection.

6.2 Recommendations for Stakeholders

Based on the evidence reviewed, the following recommendations are proposed for various stakeholders:

1. **Producers:** Implement comprehensive preventive programs addressing animal health, hygiene during milking, environmental management, and personnel training. Establish appropriate testing protocols to verify the effectiveness of preventive measures and detect potential problems early.
2. **Consumers:** Make informed decisions regarding raw milk consumption based on accurate information about potential benefits and risks. If consuming raw milk, follow recommended handling practices and avoid

serving it to high-risk individuals, particularly young children, pregnant women, elderly persons, and immunocompromised individuals.

3. **Regulatory Agencies:** Develop science-based, proportionate regulatory frameworks that protect public health while considering dairy production's diverse scales and contexts. Ensure transparent communication of risks and enable consumer access to relevant information for decision-making.
4. **Healthcare Providers:** When evaluating patients with compatible symptoms, maintain awareness of raw milk consumption as a potential source of foodborne illness. Provide evidence-based advice to patients regarding the risks associated with raw milk, particularly for vulnerable individuals.
5. **Researchers:** Address remaining knowledge gaps regarding the ecology of pathogens in dairy environments, the effectiveness of various control measures, and the potential health implications of raw versus pasteurized milk consumption. Develop improved methods for rapidly detecting pathogens in raw milk to enhance the feasibility of risk-based safety systems.

6.3 Future Research Needs

Several areas warrant further investigation to enhance understanding and management of raw milk safety risks:

1. **Microbiome Interactions:** A more comprehensive understanding of how the milk microbiome influences pathogen behavior, including potential competitive exclusion effects and quorum sensing mechanisms, could inform novel biocontrol approaches (Quigley *et al.*, 2013)^[46].
2. **Farm-Level Risk Factors:** Enhanced understanding of farm-specific risk factors for pathogen presence would facilitate more targeted preventive measures and risk-based testing approaches (Murphy *et al.*, 2016)^[38].
3. **Non-Thermal Processing Optimization:** Further development and validation of non-thermal processing technologies that can enhance safety while preserving the characteristics valued by raw milk consumers represent an important area for continued research (Buckow *et al.*, 2014).
4. **Immunological Effects:** Additional high-quality studies investigating the potential immunological effects of raw versus pasteurized milk consumption, particularly about allergic and respiratory outcomes, would help clarify an ongoing scientific debate (Brick *et al.*, 2020)^[3].
5. **Risk Assessment Models:** Development of more sophisticated quantitative risk assessment models incorporating farm-specific factors, seasonality, and consumer behavior would enhance the scientific basis for regulatory decision-making and risk communication (Costard *et al.*, 2017)^[8].

Conclusion

In conclusion, while raw milk consumption entails significant microbiological risks, a combination of evidence-based preventive measures, appropriate testing, consumer education, and regulatory oversight can help mitigate these risks for those who consume it.

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