International Journal of One Health
Available at www.onehealthjournal.org/Vol.9/No.1/1.pdf

REVIEW ARTICLE
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Ecology and epidemiology of *Salmonella* spp. isolated from the environment and the roles played by wild animals in their maintenance

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Received: 02-07-2022, **Accepted:** 03-01-2023, **Published online:** 22-02-2023

doi: www.doi.org/10.14202/IJOH.2023.1-9 **How to cite this article:** Oludairo OO, Kwaga JKP, Kabir J, Abdu PA, Gitanjali A, Perrets A, Cibin V, Lettini AA, and Aiyedun JO (2023) Ecology and epidemiology of *Salmonella* spp. isolated from the environment and the roles played by wild animals in their maintenance, *Int. J. One Health*, 9(1): 1–9.

Abstract

Salmonella is a ubiquitous organism of public health importance that causes diarrhea and other systemic disease syndromes. The ecology and epidemiology of the organism in addition to the roles played by wild animals are important in understanding its disease. Relevant published peer-reviewed literature was obtained after imputing the study's keywords into the Google search engine. The publications were thereafter saved for the study. The study revealed the ecology of *Salmonella* is directly related to its epidemiology. These were found to be either positively or negatively influenced by the living and non-living parts of the environment. Free-ranging and captive wild animals can serve as asymptomatic carriers of *Salmonella*, therefore, help to maintain the cycle of the disease since wildlife serves as reservoir hosts to over 70% of emerging zoonotic diseases. Cockroaches transmit *Salmonella* through their feces, and body parts and when ingested by birds and animals. The statistically significant over 83% of *Salmonella* isolation in lizards suggests the reptile could be a source of *Salmonella* distribution. Snakes, foxes, badgers, rodents, and raccoons have been reported to have *Salmonella* as a natural component of their gut with the ability to shed the organism often. The high occurrence (>45%) of diverse *Salmonella* serovars coupled with the fact that some of these animals were handled, kept as pets and consumed by man portends these animals as potential sources of transmission of the organism and the disease. The etiology and epidemiology of *Salmonella* are overtly affected by several environmental factors which also determine their survival and maintenance. The roles played by wild animals in the relationship, transmission, growth or interaction within and between *Salmonella* spp., the occurrence, prevalence, and distribution of the organism help maintain the organism in the environment. An understanding of the roles played by the different parts of the environment and wild animals in the ecology and epidemiology of *Salmonella* can help make informed decisions on the prevention and control of the diseases it causes. This review aimed to investigate the relationship between ecology, epidemiology, and environment, including the roles played by wild animals in the maintenance of the organism and its disease.

Keywords: ecology, environment, epidemiology, reservoir-hosts, *Salmonella,* transmission.

Introduction

Microbial ecology is the study of the interaction of microorganisms with one another, animals, plants, and the environment. This includes the study of symbiosis, biogeochemical cycles, and the interaction of microbes with anthropogenic effects such as pollution and climate change [1]. It explores the diversity, distribution and abundance of microorganisms, their specific interactions, and their effect on the ecosystem [2]. Microbial ecology also determines the patterns and drivers of microbial community distribution, interaction, and assembly since microbial community composition changes across most environmental gradients, such as geographic distance, nutrients, temperature, moisture levels, salinity, oxygen availability, pH, and day length [3].

Microbial epidemiology is the study of the determinants, occurrence and distribution of health and disease in a defined population as it relates to the replication of the organism in host tissue which may cause disease [4]. It allows traceback of disease to the origin, monitors the spread of disease-causing strains, studies population dynamics of the disease strain, discerns endemic/enzootic infections from those that are epidemic/epizootic, detects the presence of multiple strains in population and individuals, identifies the mode of transmission of disease agents from host to host and also focuses on other epidemiological agents [5].

Diverse environmental conditions strongly shape microbial behavior, ecology, and evolution.

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The steady environmental fluctuations have pervasive characteristics on microbial life [6]. High species diversity is the ability of hundreds of species to coexist. This is maintained by microscale partial heterogenicity, resource partitioning, dormancy, and environmental fluctuations [7]. Microbes have been living on the planet for billions of years and have persisted through several planetary changes, always figuring out ways to adapt to environmental changes [8].

Salmonella enterica is a Gram-negative, motile, non-sporulating aerobic or facultative anaerobic, rod-shaped bacterium from the family *Enterobacteriaceae*. They may survive temperatures between 2°C and 54°C, pH 3.7–9.4, disinfectants such as acetic acid, and propionic acid and extended periods in dry environments [9]. The organism is one of the four key global causes of diarrheal diseases responsible for about 1.35M infections, 26,500 hospitalizations and 420 deaths in the United States every year with food as the source of most of the illnesses [10]. Salmonellosis is a global public health concern because the World Health Organization reported that worldwide every year, almost one in 10 people fall ill and 33M of healthy life years are lost, 550M people fall ill every year, including 220M children under the age of 5 years [11].

Salmonella occurrence has been reported in animals, humans, and the environment with many biotic and abiotic factors contributing to the ubiquity of the organism in the environment where some serovars may be associated with specific ecological niches [12, 13]. Incidence and biodiversity of salmonellae occur in an aquatic environment, domestic and agricultural waste, farm animals/environment, domestic/wild animals, and free-living wild birds [14].

Wild animals are natural wildlife that are not domesticated and not under the control of humans. Wildlife can be reservoirs of infectious agents, favoring the quadridirectional transmission of pathogens between wild, domestic animals, humans, and the environment [15–17].

This review highlights the roles wildlife plays in the occurrence and maintenance of *Salmonella* in the environment in relation to the ecology and epidemiology of the organism and its disease.

Ecology and Epidemiology of *Salmonella*

Ecology is the relationship between and within organisms and their environment while epidemiology is the study of the incidence, prevalence, and distribution of diseases and other factors associated with health. Salmonellosis is considered a consequence of interrelated factors, such as food, environment, vectors, people, utensils, equipment, production line, animal transit, and animal reservoirs [18].

Ecology and Epidemiology of *Salmonella* in Relation to Non-living Part of the Environment

Salmonella species are key pathogens that have been associated with environmental sources and transmission through various means [19–21]. The environment and wildlife have also been well-documented to be important sources of this pathogen [20, 22, 23]. For example, in the US, environmental sources of *Salmonella* Newport appear to be responsible for repeat contamination of tomatoes grown on the Eastern shore of Virginia [24]. The knowledge of the roles natural areas may have in harboring *Salmonella* for potential transmission to food, animals, and man is of utmost importance [25]. The potential reservoirs of *Salmonella* in the environment include water and soil which humans may be exposed to through primary contact and ingestion. These reservoirs may account for cases of salmonellosis in which there is no known food source [23, 26].

Salmonella species loading into the ecosystem are influenced by different seasonal environmental parameters. The understanding of these parameters is important in predicting and preventing the transmission of the pathogen [27, 28]. A higher prevalence of salmonellosis in humans and animals may cause an increase in the density of *Salmonella* in surface waters and the environment [29]. The increased density of *Salmonella* on surface water has been reported to vary depending on the season, suggesting that rainfall may influence the transport and spread of *Salmonella* to the environment [30–32]. Higher *Salmonella* density has also been associated with an increase in water temperature and low stream flow [33]. Researchers have suggested that variations in the density and prevalence of *Salmonella* may be affected by seasonality [34].

The seasonality of fecal shedding is critical to understanding the flow and distribution of *Salmonella*. In the US, shedding by humans and food animals, especially cattle and swine, can approach zero during winter months and reaches its peak in summer and early fall [35–37]. Other researchers found that the highest incidence of *Salmonella* in farms occurs during the late fall (October-December) instead of the summer [38].

A positive correlation was recorded between an increase in *Salmonella* shedding and physical temperature as opposed to the animal's internal temperature, which was fairly constant [39].

Other inherent host factors that affect the seasonality of *Salmonella* shedding include thyroid hormones and melatonin levels [40, 41].

Ecology and Epidemiology of *Salmonella* in Relation to Living Part of the Environment

Salmonella are poly-pathogenic agents which do not cause infection in all members of an observed species or population [42]. They can be borne as harmless commensals in some sectors of the population, while in other individuals, the same microbe causes devastating and fatal illnesses [19]. Despite considerable efforts and an increased understanding of how the *Salmonella* infection develops in the clinical course, many key questions concerning *Salmonella*

infection remain unanswered. For example, the ability of *Salmonella* to destroy the host's cells has been a subject of century-long discussions [43].

Microorganisms usually penetrate the animal or human victims using one of the main channels of interactions with the environment, which are nutritional, respiratory, and sexual [43]. These ecological interphases are strongly predetermined by previous evolutionary co-adaptation of both microbe and victim and are characteristic of every kind of "microbe-victim" ecological system [43]. In the case of the "*Salmonella*-victim" ecological system, microbes penetrate the victim's body through the nutritional channel of its ecological connections, after which the victim's body becomes the source of *Salmonella* multiplication and further transmission. The victim's body becomes the next source of the next circle of *Salmonella* transmission in the body of the next victim, thus, the aptitude for regular interaction with this kind of infectious agent is characteristic of omnivores and carnivores compared to herbivores [44, 45].

Other Factors Affecting the Ecology of *Salmonella*

There have been many research work aimed at understanding the effect of different types of stress on populations of *Salmonella,* especially dietary and transportation stresses [39, 46]. Well-fed cattle had fewer ruminant *Salmonella* populations compared with those starved for 2 days [47]. The longer time between leaving the farm of origin and the time of slaughter led to an increased incidence of *Salmonella* in the rumen and feces of cattle [48]. Several hours of transporting pigs in trucks have been reported to significantly increase Salmonella's fecal shedding [49–51]. More *Salmonella* were also reportedly found on the hides of animals at slaughter compared to levels at the farm [52]. Stress-associated feed withdrawal or starvation has been reported to cause increased susceptibility to *Salmonella* Enteritidis infection marked by increased intestinal shedding and dissemination of the organism to internal organs such as the liver, spleen, and ovary [53–56]. This has also been reported to increase the incidence of *S.* Enteritidis-positive eggs [57].

Wild Animals in Zoos, Parks, and Free Range; Role in the Epidemiology of *Salmonella*

Wildlife refers to wild plants and terrestrial animals that owe their existence to natural phenomena or to a process that occurs automatically. They include mammals, birds, and bees. Wild animals encompass free-range wildlife, migratory wildlife, captive wildlife (animals in zoos and wildlife parks), and feral animals (wild pigs, *Sus scrofa*) [58, 59].

In today's global environment, the management and suitable utilization of natural resources, including wildlife, is a major challenge facing governments and their national economies. Effective management of these resources will attract international tourists; earn foreign exchange for the country, thereby contributing positively to the socioeconomic development of the country [60].

Zoological Garden and Wildlife Park

A zoological garden is a scientific and educational institution where animals are restricted within enclosures to some system of taxonomic classification, bred and displayed to the public with the purpose of advancement and diffusion of knowledge and love of animals using living animal collections, library, laboratories, and lecture halls, in some cases zoological museums together with scientific and administrative staff is a scientific and educational institution where animals are restricted within enclosures to some system of taxonomic classification, bred, and displayed to the public with the purpose of advancement and diffusion of knowledge and love of animals using living animal collections, library, laboratories, and lecture halls, in some cases zoological museums together with scientific and administrative staff [61]. A zoo can also be defined as a permanent establishment where living, wild animals are kept for exhibition to the public for 7 or more days a year, with or without admission charge. This will include aquaria; sanctuaries; bird gardens (including birds of prey); safari parks; and any collections of living species on display to the public. This definition also applies to exhibitions yet to be licensed or which may be exempted from licensing control. It excludes pet shops or circuses [62].

Zoological gardens are usually established for public service (socio-cultural, economic, recreational, and aesthetic services), education, conservation, and research [62]. The increasing number of animal species that would have gone into extinction may be establishing self-sustainable populations in the zoological gardens. The gardens, thus, present a popularity-driven, skewed representation of the animal kingdom to the public serving the purpose of conservation [60].

Zoos are evolving into economically important professionalized institutions that publicly display the zoological spectrum from tiny invertebrates to charismatic mega vertebrates [63]. They play important roles in developing techniques for *ex situ* breeding, animal welfare, global wildlife disease monitoring, response and intensive population management, which is a science that is increasingly important for biodiversity management [63].

Wildlife parks are protected areas where both captive and free-ranging wildlife are kept for the protection of the animals and offering of exclusive recreation to the public [64].

Role of Wild Animals in the Epidemiology of *Salmonella*

Approximately 60% of all human pathogens are zoonotic and originate from animals, in which wildlife plays a key role [65]. Free-ranging and captive wild animals may serve as asymptomatic carriers of enteric

pathogens such as *Salmonella* [66]. There are approximately 1,415 infectious agents causing diseases in humans, out of which 868 (61%) are known to be zoonotic. It is also important to note that more than 70% of emerging zoonotic diseases have wild animals as reservoir hosts [67]. Wildlife species have the potential to contaminate the environment, especially waterways; the microorganisms can also be transmitted through evisceration, processing, and consumption of improperly cooked game [68].

Wild animals are important in maintaining the source of infection as asymptomatic carriers, causing sporadic cases or local epizootics of salmonellosis by contamination of feeding places [69, 70]. *Salmonella* spp. can be shed in the feces of apparently healthy wild animals for a long time and can be isolated at virtually every step of the game–meat chain [71, 72]. Wildlife can additionally be involved in human salmonellosis taking part in the ecology of these bacteria and thereby contributing to the persistence of bacteria in the environment [73]. The study of pathogens in captive animal populations is critical for the implementation of programs for the prevention, control, and surveillance of diseases, as well as for developing public and animal health policies [74].

Role of Wild Birds in the Epidemiology of *Salmonella*

Salmonella spp. are usually transmitted from captive or pet birds to humans through direct or indirect contact with sick or asymptomatic birds [75]. Several isolations of *Salmonella* from wild birds in and around residential houses underscore their importance in the epidemiology of human and animal salmonellosis [76–80].

Apart from shedding *Salmonella* in their feces, migratory birds have also been reported to carry *Salmonella* on the pads of their feet, which are important in the epidemiology of the disease [81]. Wild birds, apart from direct contamination, may indirectly contaminate water, crops, meat, egg, milk-producing animals, and milk products, thus serving more as dispersal agents of *Salmonella* [82]. Wild birds can serve as animal vectors, spreading the disease along migration routes and transferring zoonotic bacteria throughout large parts of the world in their fecal droppings [83, 84]. Other studies [78, 81] suggest that wild birds do not present a major public health hazard given the low excretion of *Salmonella*; this is in contrast to the study by Benskin *et al*. [83];

Role of Cockroaches (*Blatta* and *Periplaneta* spp.) in the Epidemiology of *Salmonella*

Cockroaches are known to carry diverse pathogenic bacteria flora, although their role in the direct transmission of infection is seldom established [85–87].

Cockroaches have been previously identified as carriers of *Salmonella* but do not suffer from salmonellosis; the free wandering movements of cockroaches from one location to the other probably aid their ability to spread the disease [88, 89].

Isolation of an appreciable number and many serotypes (R types and phage types) of *Salmonella* spp. from cockroaches captured in human dwellings and livestock premises indicates that these domestic insects can pose a problem in the spread of salmonellosis, particularly in hospitals, houses, and restaurants [89, 90]. It has been suggested that contamination of food and water sources with cockroaches' feces may lead to epidemics [89]. Cockroaches may play important roles in the epidemiology of *Salmonella* because they are natural prey for a variety of birds and animals, including amphibians, reptiles, rodents and domestic/wild birds [84, 89]. They also form a part of human food in certain countries and cultures, while others use them for medicinal purposes [89].

Role of Frogs, Squamate/Squamata, and Lizard in the Epidemiology of *Salmonella*

Frogs have been identified as natural reservoirs of *Salmonella* [91]. Globally, there has been an increase in squamates, particularly lizards and snakes, being kept as pets [92].

Squamates have experienced increased encroachment of their ecosystem due to increased human population and urbanization, which may lead to an increase in the transmission of salmonellosis. *Salmonella* is often detected in captive reptiles and reports of salmonellosis linked to reptile pets are increasing [93].

A study in Malaysia demonstrated that 83.3% of captive lizards (*Iguanidae*, *Agamidae*, *Scincidae*, *Gekkonidae*, and *Varanidae*) and 25% of wild lizards (*Agamidae*, *Scincidae*, *Gekkonidae*) were positive for *Salmonella* [94]. The statistically significant ($p < 0.05$) *Salmonella's* higher carriage rate of captive lizards than wild lizards could be attributed to the horizontal transmission of *Salmonella* from humans and other animals to captive lizards [92, 95]. The globally increasing demand for exotic pets, especially squamates has the potential for international importation of diseases and organisms they transmit, like *Salmonella* [96, 97].

Role of Snakes in the Epidemiology of *Salmonella*

Wildlife snakes carry many bacteria and parasites that differ considerably according to geographical locations and source species [95, 98]. They often shed *Salmonella* spp., which are often considered natural components of reptile gut flora [96, 99, 100]. Studies have shown a high occurrence of diverse *Salmonella* serovars belonging mostly to *S. enterica* [101]. Uncommon subspecies, *S. enterica* subspecies *diarizonae* 40:i: z 53, z54 and 48:k z57 have been reported in free-living adders and humans [101, 102]. *Salmonella* shedding in snakes draws attention to possible zoonotic and epidemiological impacts, much more so in countries where snakes are handled, kept

as pets and consumed by omnivorous animals, including man [101].

Role of Red Foxes and Badgers in the Epidemiology of *Salmonella*

Red foxes (*Vulpes vulpes*) and badgers (*Meles meles)* can be considered indicators and spreaders of zoonotic infections due to their feeding habit [103]. They have an omnivorous diet that includes prey and plants. They scavenge around human waste disposal sites and dustbins, exposing them to many potential sources of *Salmonella*. In a study designed to isolate *Salmonella* from red foxes and badgers in Italy in 2014, a prevalence of 45.1% was recorded, of which 5.7% and 11.76% of the serovars, respectively, are responsible for most cases of human salmonellosis [104].

Role of Rodents in the Epidemiology of *Salmonella*

While rodents are often associated with infrastructural damage and eating or spoiling of stored feed and products, their zoonotic risks are frequently underestimated [105]. Wild rodents can be reservoirs and vectors of several agents that cause disease in farm animals and humans [106, 107].

Laboratory studies prove that rodents can, in principle, be infected with *Salmonella*. Several studies have been undertaken to estimate the prevalence of *Salmonella* in wild rodents [108].

The degree of contamination and transmission risks may differ substantially between different rodents' habitats, nature (woodland, grassland, etc.), urban environments, and farm environments. Rodents living in farm and urban environments have been reported to have higher contamination and transmission rates than those living in the natural environment [108, 109]. Infected rodents can shed *Salmonella* at up to 10^5 Colony-forming unit/fecal pellets [110].

Role of Raccoons (*Procyon lotor*) in the Epidemiology of *Salmonella*

Raccoons can be asymptomatic carriers of various bacterial agents, including *Salmonella* that can affect human and domestic animal health [74, 111–113]. They shed *Salmonella* spp. in their feces and more importantly, can carry and transmit the organism through their paws since they commonly grasp, handle and manipulate food with their front paws before consuming it [114].

Role of Other Wildlife in the Epidemiology of *Salmonella*

Salmonella enterica serotypes have been isolated from numerous species of free-living and captive mammals with major emphasis being placed on studies of agricultural animals and avian populations [111]. Increasing attention has turned to wild animals such as skunks, opossums and deer as the prevalence of *Salmonella* in these wildlife populations is unknown due to the difficulty in sampling animals for epidemiologic studies, which poses a challenge [115].

Role of the Wild Game (Meat) in the Epidemiology of *Salmonella*

Wild animal (game) meat represents an important source of protein for many people, particularly in Africa and some other parts of the world. It is also known as bush meat. Wild game meat is derived from wild animals hunted under uncontrolled conditions, transported to distant markets under rudimentary or unhygienic conditions and often eviscerated over 24 h after death. The transportation, handling, processing, and consumption of wild game have been reported to play important roles in the epidemiology of *Salmonella* [116].

Role of One Health Approach in the Epidemiology of *Salmonella*

There is a need for one health clear-understanding and approach in the epidemiology of *Salmonella* because of the connection and relationship between *Salmonella* incidence and infection in humans, animals, plants, and the environment [117]. Experts in food safety, zoonotic disease control, laboratory services, neglected tropical diseases, environmental health, and antimicrobial resistance sectors are among the professionals whose work is pertinently required for an effective one-health approach to the prevention and control of salmonellosis [118].

One health epidemiological studies of *Salmonella* are essential to document information related to the organism and its infection in various spheres of life, which could eventually result in the formulation of a consolidated *Salmonella* control policy by the environment, human, and veterinary health sectors [13].

Conclusion

The relationship between/within *Salmonella* and their environment has a direct bearing on the occurrence, prevalence, and distribution of salmonellosis, including other factors associated with health. This relationship is the intersection between *Salmonella* ecology and epidemiology. Non-living parts of the environment such as water, rainfall, soil, temperature, and weather affect *Salmonella* ecology and epidemiology. Host-cell-related factors such as stress, diverse etiology, and those related to the microorganism which are usually predetermined by previous evolutionary co-adaptation of the microbe and the host has a contributory effect on *Salmonella* ecology and epidemiology. Free-range, migratory, and captive animals are part of wildlife, which includes mammals, birds and bees on free-range, kept in zoological gardens and wildlife parks are important in the epidemiology of *Salmonella*. Wild animals could be symptomatic or asymptomatic carriers of *Salmonella* and sources of transmission of salmonellosis from the cages they are kept to the free environment they are found. They

could transmit the organism to the countries and continents they migrate to. Cockroaches, frogs, lizards, snakes, foxes, badgers, rodents, raccoons, skunks, opossums, and deer have all been reported to play important roles in the epidemiology of *Salmonella*. Wild game or bush meat is an important part of many cultures in Africa, Asia, and many other parts of the world. The unhygienic and uncontrolled handling of the game from wild to fork has been reported to serve as a major source of transmission and distribution of *Salmonella*. One health epidemiological approach is important for the control and prevention of salmonellosis to be effective.

Recommendations

There is a need for better knowledge of the ecology and epidemiology of *Salmonella* to facilitate the understanding of the survival and interaction of the organism with one another. More research work on the occurrence, distribution, and related health factors of diseases caused by the organism needs to be carried out. Other studies should include the effect of the environment on Salmonella and salmonellosis to further understand the microbial agents they are either resistant or susceptible. Prevention of contact with infected wild animals/birds and contaminated environments to limit the further spread of the organism and disease should be encouraged. There should be continual surveillance of wildlife populations to determine the *Salmonella* spp. in circulation in comparison to those in the human and domestic animal populations. There is an urgent need for the implementation of one health for better understanding, control, and prevention of salmonellosis.

Authors' Contributions

OOO, JKPK, JK, and PAA: Designed the review. OOO and JKPK: Drafted the manuscript. JKPK, KJ, PAA, AG, AP, VC, AAL, and JOA: Edited the manuscript. All authors have read, reviewed, and approved the final manuscript.

Acknowledgments

The University of Ilorin and Ahmadu Bello University provided the necessary facilities for the study. The authors did not receive any funds for this study.

Competing Interests

The authors declare that they have no competing interests.

Publisher's Note

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