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Aeolian contamination of fruits by enteric pathogens: an unexplored paradigm☆

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Dust, fine particulate matter suspended in air, represents an understudied vehicle for microbial dispersal in agricultural environments and fruit contamination by microorganisms pathogenic to humans. Dust not only affects biological processes in plants, such as stomatal gas exchange, but also the plant surface microbiome. While the risk of growing fruits and vegetables in proximity of livestock operations is well recognized, a full understanding of the mechanisms by which fresh produce become contaminated remains incomplete without the consideration of dust. Currently no recommendations on the microbiological quality of air in produce production environments exist. This review explores the association between carpoplane (fruit surface) contamination by enteric bacterial pathogens and the ability of these pathogens to survive and disperse with aerosolized dust.

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Introduction

Historically, 'bad air' or miasma was considered as a common source of illness until the importance of water as a vehicle for cholera was elucidated by Dr. John Snow in London in the mid nineteenth century [1]. Water is considered a major vehicle for transmission of disease in plants. Water also plays a crucial role both in the cultivation and post-harvest processing of fruits and vegetables. Food safety research efforts have hence focused extensively on understanding the effects of contaminated water and soil on the microbiological quality of fresh fruits and vegetables. Edaphic contamination of produce surfaces is also commonly linked to soil dispersal facilitated by water, such as splashing of soil during rainfall or irrigation, or from runoff from soils containing high populations of enteric pathogens [2]. The possibility of wind-mediated dispersion of pathogens in the contamination of produce has received far less attention.

Although significant advancements in understanding the sources, routes and mechanisms [3,4••,5,6] of fruit contamination, and subsequent preventive controls to minimize risks have been achieved [7], the number of reported outbreaks of foodborne illnesses associated with the consumption of fresh fruits has been on the rise [8–20]. Within the last five years, cucumbers, cantaloupes, apple, mango, papaya, and stone fruits have been involved in foodborne outbreaks and recalls due to contamination by enteric pathogens. While the implication of fresh fruit in reported outbreaks and recalls is unequivocal, the sources of fruit contamination for the majority of these incidents have not been identified. Furthermore, recent outbreaks, especially those associated with tree fruits, have challenged the current consensus of tree fruit being a low-risk food and thereby our understanding of risk assessment. Hence, the requirement for a paradigm shift toward recognizing vehicles and sources other than water and soil-associated transmission of pathogens in the fruit production continuum is essential.

Dust, broadly defined as fine particulate matter resulting from wind erosion on land surfaces and suspended in the air, is an inseparable component of the atmosphere. The suspended particles are transported large distances and are deposited over oceans and land surfaces with important consequences on climate, biogeochemical cycles and human health on a regional to global scale [21,22]. Wind erosion in areas where surface soil contains traces of chemical, radioactive or biological contaminants are known to increase contaminant concentrations in airborne

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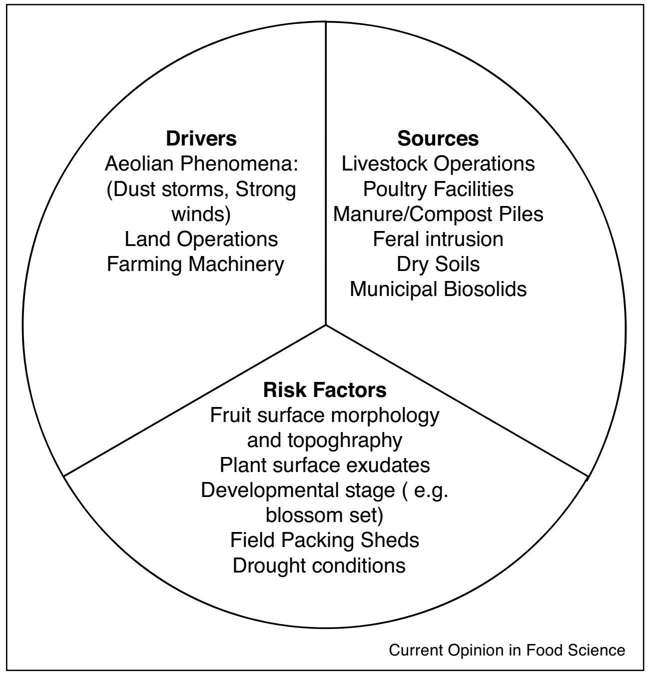
dust [23]. Of particular significance to this review is the potential dust-mediated transport of foodborne pathogens from remote sources to plant crop surfaces [24].

Dust deposition onto crops during field cultivation is inevitable as plant surfaces serve as a major aerosol sink [25]. Studies have indicated that dust can serve as a vehicle for bacteria [4••,24,26••]. Aeolian or wind-driven distribution of dust in agricultural environments could also impact food safety when the sources of dust include particles from natural (soil, decaying vegetation, feral animal droppings) and man-made (manure-amended soils, silage, municipal sewage-based biosolids, composting and animal production facilities) reservoirs of human pathogens. It is estimated that dust levels in a field during farm operations could reach 35 mg m^{-3} of air [27]. While the population dynamics of enteric pathogens in soil and water is well characterized, the evidence for dust-associated transmission of foodborne pathogens is limited. The objective of this review is to provide evidence that the aeolian distribution of dust is a potential risk factor affecting food safety in the field, farm and processing facility.

Figure 1



Sources, drivers and risk factors contributing to dust associated contaminated of fruits and vegetables.

Bacterial attachment and survival on dust

Bacteria can attach to surfaces due to their surface charge, polymeric substance production, cell hydrophobicity, Van der Waals forces, electrostatic interactions and surface structures such as fimbriae [28–30]. Many foodborne pathogens have unique genetic and physiological strategies to overcome desiccation stress [31,32] contributing to their survival in dust or plant debris [33]. Foodborne pathogens can survive and grow in decaying vegetation, soils and sediments resulting in their potential distribution by dust [4••,33,34].

Wind erosion occurs when wind shear at the soil surface exceeds the strength of soil aggregates and their resistance to detachment and transport [22]. Typically, dust emissions are due either to the direct suspension of fine-sized particles present in the soil or to the production and entrainment of dust-sized particles via abrasion of soil particles [22]. Dust is generated also during field operations such as field tilling, ripping and land planning especially when the soil is dry [35]. Soil operations on farms can result in respirable dust emissions of 10.3 mg m^{-3} [35] while composting can result in inhalable dust concentrations $\geq$10 mg m^{-3} with airborne Gram-negative bacteria reaching 5 log CFU m^{-3}. Dust release generated by land application of manure or municipal biosolids could be composed of the microflora characteristic of the source. Operation of farm equipment, such as a front-end loader dropping compost into a hopper also contributes toward dust generation during land application operations [36,37]. Dust particulates aerosolized during disk-incorporation operations were shown to travel distances of 165 m [38]. Livestock activity was shown to generate dust. Hence aerosolized dust can travel longer distances depending on wind characteristics [39], fruit-growing areas in proximity are subject to aerosol contamination (Figure 1). Indeed, investigation of the 2006 spinach outbreak of *Escherichia coli* O157:H7 linked contamination of spinach to the proximity of livestock-feeding operations [40]. *Salmonella* has been isolated from poultry dust and farms where livestock are grown [41,42]. *Listeria* spp., including *L. monocytogenes*, were recovered from the air during beef hide and sheep fleece removal [42]. *L. monocytogenes* can survive in a dust surrogate for 151 days [34]. *E. coli* O157:H7 can be found in the hides of cows and can be disseminated during dust dispersal [43] that occurs during cattle operations or when manure is added to soils [44]. Hence, the activities that result in dust dispersal require monitoring whether on the farm, field or processing facility.

Evidence for dust as a vehicle for pathogens in contamination of foods, livestock and agricultural environments

In a 1998–1999 multistate outbreak of listeriosis, the dust from a construction site served as a vector for *L. monocytogenes* transmission to Ready to Eat (RTE) meats prior to packaging [45]. De Roin *et al.* [34] showed that *L. monocytogenes* attached to and survived in desiccated sand particles, which served as dust-like vectors for contaminating RTE meat, for up to 73 days from the inoculum preparation. Foong *et al.* [46] found that the pathogen was able to survive for up to 2 months on a dried, nutritionally depleted medium, demonstrating the ability of *L. monocytogenes* to survive in low moisture hygroscopic environments. *Salmonella* persisting in poultry facilities can be aerosolized and aerially dispersed due to flock activity disturbing fluff from feather and litter. Chinivasagam *et al.* [47] assessed the levels of *Salmonella* and *Campylobacter* in aerosols present within and outside poultry sheds. It was found that the levels of bacteria in air are related to the level of the same bacteria in litter. The *Salmonella* serotypes isolated from the litter were also isolated from aerosolized dust [47]. *Salmonella* also survived on spinach leaves that were experimentally contaminated with turkey manure dust indicating the possibility of dust-mediated transfer of animal or bird feces and associated bacteria [48••]. Lues *et al.* [49] studied the microbial composition of a chicken slaughtering facility over a four-month period. Highest microbial counts were observed in receiving, killing and defeathering areas. A strong correlation was found between *Salmonella* presence and airborne particulates. Interestingly, dust was the only environmental factor of significance to influence the dispersal of *Salmonella* in this chicken slaughtering facility [49].

The contamination of insulated and non-insulated poultry, dairy and pig houses was surveyed for the presence of bacteria, endotoxins (an indicator of Gram-negative bacterial presence) and dust content. The concentrations of dust in poultry houses, pig houses and dairy houses ranged between 8.2–13.6, 5.5–8.2 and 2.5–7.9 mg m^{-3} respectively, and the air of pig and poultry houses had higher contamination of endotoxins and bacterial population than both insulated and uninsulated cow sheds. A strong correlation between airborne bacterial population and endotoxins was observed in poultry houses with endotoxin concentration in poultry houses ranging from 80 to 1280 ng m^{-3}. A correlation between the aerosolized dust, bacterial populations and endotoxins in the air indicated that farming operations, hygiene and the type of animals present in a facility could affect the quality of the surrounding air [41].

Gram-negative bacteria such as *Salmonella* and *E. coli*, could lose their ability to be cultured when exposed to environmental stressors and sunlight but retain viability [50], making the detection of endotoxins a convenient approach for evaluating the microbiological quality of air. On the other hand, staphylococci are more resistant to desiccation and thus could be considered as a better indicator organism for the microbiological quality of air. Staphylococci are common dwellers of animal hides and nares [51]. The risk of airborne dispersal of methicillin-resistant *Staphylococcus aureus* (MRSA) from animal livestock facilities should be an important consideration to prevent the spread of antibiotic resistance genes in the environment. MRSA, detected in pig facilities, was also recovered from soil and air samples at a distance ≤300 m from the contaminated animal facility [52]. Seasonality was a significant factor that affected the distribution of MRSA, with highest transmission occurring in the summer. MRSA recovered from air samples (21% positive) were genetically similar to those isolated from the farm, demonstrating the airborne transmission from the farm to the proximal environment [53]. The increased transmission of MRSA in the summer was proportional with a 30% increase in dust particulate in the facility during this season [52]. Dust generation during cattle livestock operations can also serve as a vehicle for bacterial transfer. The hides of 250 cattle were sampled for the presence of *E. coli* O157:H7 and *Salmonella* after exposure to naturally generated dust clouds derived from pen floor dust. The generation of dust caused an increase in *E. coli* O157:H7 and *Salmonella* counts on cattle hides. Samples of aerosolized dust were also positive for the pathogens when dispersed in the air due to animal activity [43].

Evidence for aeolian contamination of fresh fruits

Although direct application of untreated animal manure or fecal slurry to soil during the production of fruit and vegetable crops has been restricted, this practice is acceptable in production of grains, beans and cotton. This practice greatly contributes to the dispersal of zoonotic pathogens across large areas [53]. The wind-mediated dissemination of plant pathogens was described when cotton leaves infected with *Xanthomonas malvacearum* were scattered across 40 ha in 20 min by a single whirlwind [54]. Fruit surfaces can harbor microorganisms deposited to their surface from dust particles or can internalize enteric pathogens when blossoms are contaminated [4••,55]. Airborne dust particulates were demonstrated to be able to serve as a vehicle of *Salmonella* cross-transfer from soil to tomato blossoms. Biophotonic imaging of tomato blossoms contaminated with airborne soil particulates (dispersed using pressurized air) that were inoculated with bioluminescent *Salmonella* Newport, indicated presence of the pathogen on the petals, sepals and the calyx of the blossom [4••]. Tomato blossom contamination resulted in *Salmonella* colonization of the surface and within the fruit [4••] indicating the importance of monitoring produce for pathogen presence after events such as dust storms. *Salmonella* strains from tomato outbreaks can form biofilms on quartz particles indicating that sediments might serve as a stratum for biofilm formation. Dried sediments could be dispersed by aeolian phenomena from river beds, ponds, ditches and lagoons.

A study of the microbiome of the apple phyllosphere revealed the presence of both culturable and non-culturable bacteria on leaves and shared 98% sequence similarity with dust and windborne bacterial species [56]. Once deposited on the fruit surface, foodborne pathogens can grow due to the presence of sugars, amino acids and fatty acids in fruit exudates [57]. The air may in fact be a more important reservoir for plant surface microbiota than other agricultural inputs that have been traditional identified as important pathogen sources. In a tomato surface microbiome study assessing the influence of various soil amendments on the microbiomes of various tomato plant structures, proximity to farm roads, but not soil amendments was identified as a factor influencing tomato fruit microbial community diversity [58•]. Dust from passing vehicles may have introduced distinct bacterial taxa to tomato vines planted in rows flanking the road compared to the interior rows in the field.

The occurrence of foodborne pathogens on tree fruits that are at a distance from the ground provides even more evidence in favor of dust associated microbial contamination [59]. In a surveillance study on the pre-harvest prevalence of enteric pathogens in kiwifruit, *S. aureus* and *E. coli* incidence was 3.9% and 18.3%, respectively [60]. During the assessment of kiwifruit orchards in a consecutive year, *E. coli* was recovered from 13% of the fruit samples and 9% of the air samples collected in the same orchard [61••]. Aeolian distribution of foodborne pathogens with contaminated dust is likely when farms are located near pastures or produce is grown near plots that have been amended with manure (Figure 1) [62]. *E. coli* contamination of apples on fruit trees was also reported in high risk apple orchards, one of which was in close proximity to a pasture [62]. In a surveillance study of stone fruit orchards conducted in 2014 and 2015, *L. monocytogenes* was recovered from 1.1% of fruit samples (Macarisin *et al.*, abstract in *J Food Protect* 2016, 79 (S):179). In a follow-up study assessing the incidence of *Listeria* spp. in apple orchards, *Listeria* spp. were detected in 29.6% and *L. monocytogenes* in 1.7% of apples sampled during the 2016 growing season (Sheth *et al.*, abstract in *J Food Protect* 2017, 80(S):97). While non-potable fruit wash water, handling and bird droppings have been suggested as possible sources of contamination of fruit, the possibility of aeolian contamination of fruit or blossoms, even though highly plausible, remains largely uninvestigated.

Challenges and opportunities in research of dust-associated transmission of enteric pathogens

Acknowledgment of dust as a potential vehicle of foodborne pathogens would be an important step toward further fortifying produce safety. The potential of antibiotic resistance strains being dispersed from animal facilities to farms and the surrounding environment provides further impetus to develop standards for the microbiological quality of air in these operations. Knowledge gaps exist in our understanding of wind-associated dispersal of dust and in effective practices to reduce dust dispersal. More studies are required for an accurate assessment of the dynamics and frequency of dust-associated dispersal of foodborne pathogens from agricultural activities, feed lots, and animal production facilities. The data can help in the development of predictive models and quantitative microbial risk assessment to further improve pre-harvest safety of fruits and vegetables. Bridging these gaps will help in the development of standards for air quality, which currently do not exist, in the fruit production continuum.

Dust particles could be hygroscopic in nature and could result in rapid desiccation of the microorganisms being hosted. Desiccation stress has been associated with lowered detection of foodborne bacterial pathogens because of their entry into a slow growing state or a change in morphotype known as the filamentous state [46,50,63].

Currently the use of Whole Genome Sequencing and nucleic acid amplification based protocols might not be able to distinguish between dead, stressed-slow growing and live cells, a distinction of importance from a regulatory perspective. The complex composition of aerosolized dust and its distribution dynamics provides experimental challenges with enteric pathogens. The development of non-pathogenic surrogates with fluorescent and luminescence detection profiles can help in studying cross-transfer to fresh produce surfaces and spatial distribution across the phyllosphere in real-time.

Conclusions

Major outbreaks of foodborne illnesses associated with the consumption of whole fruits have been primarily attributed to environmental contamination, while contamination sources or/and vehicles remain unknown. Recent surveillance studies for distribution of major enteric pathogens in tree fruit production environments reported occurrence of *L. monocytogenes*, *Salmonella*, *Staphylococcus* and *E. coli* in tree fruits and orchard air. Considering that tree fruits are not in contact with soil, and the surveyed orchard did not use overhead irrigation, the feasibility of airborne particulate matter such as dust carrying the pathogens should not be disregarded as a potential vehicle of contamination. The reports demonstrating the ability of enteric pathogens to survive in dust and dust-like matrices, together with the multistate outbreak of listeriosis linked to dust-associated contamination of RTE food in 1999, suggest the potential for aeolian contamination of fruit grown up off the ground.

The distribution of dust is a dynamic process affecting climate and crop production. Dust generated from agriculture and animal production activities have the potential to harbor foodborne pathogenic bacteria (Figure 1). Evaluating the microbiological quality of air produced from these activities would provide insights into the aeolian contamination of produce. Climatic changes (e.g. increase in aridity, droughts) and recurrent disturbances (e.g. deforestation, overgrazing, fires) have rendered soils in many agroecosystems highly susceptible to wind erosion and subsequent dust emissions [22]. Recommendations that discourage crop production close to forested areas with the aim of reducing animal intrusion may need to be reconsidered in high-risk areas of low air quality where tree canopies could act as buffers to aerosolized particulate matter. Considering the potential impact of dust-mediated contaminants on food safety, understanding the mechanisms and trajectories of dust emission from agricultural and livestock production systems is vital.

Conflict of interest statement

The authors declare no conflict of interest.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Halliday S: **Death and miasma in Victorian London: an obstinate belief**. *BMJ* 2001, **323**:1469.

2. Cevallos-Cevallos JM, Danyluk MD, Gu G, Vallad GE, van Bruggen AH: **Dispersal of *Salmonella* Typhimurium by rain splash onto tomato plants**. *J Food Prot* 2012, **75**:472-479.

3. Zheng J, Allard S, Reynolds S, Millner P, Arce G, Blodgett RJ, Brown EW: **Colonization and internalization of *Salmonella enterica* in tomato plants**. *Appl Environ Microbiol* 2013, **79**:2494-2502.

4. •• Dev Kumar G, Williams RC, Al Qublan HM, Sriranganathan N, Boyer RR, Eifert JD: **Airborne soil particulates as vehicles for *Salmonella* contamination of tomatoes**. *Int J Food Microbiol* 2017, **243**:90-95.

The results from this study indicate that dust can serve as a vehicle for tomato blossom contamination. Tomato blossoms cross-contaminated by dust, harboring the pathogen, led to surface contamination of the fruit. Some fruits, which developed from dust-contaminated blossoms, were also internally contaminated by *Salmonella*.

5. Chen Y, Evans P, Hammack TS, Brown EW, Macarisin D: **Internalization of *Listeria monocytogenes* in whole avocado**. *J Food Prot* 2016, **79**:1440-1445.

6. Macarisin D, Wooten A, De Jesus A, Hur M, Bae S, Patel J, Evans P, Brown E, Hammack T, Chen Y: **Internalization of *Listeria monocytogenes* in cantaloupes during dump tank washing and hydrocooling**. *Int J Food Microbiol* 2017, **257**:165-175.

7. Food and Drug Administration: **Standards for the growing, harvesting, packing, and holding of produce for human consumption**. *Fed Reg* 2015, **80**:74353-74672.

8. Angelo KM, Chu A, Anand M, Nguyen TA, Bottichio L, Wise M, Williams I, Seelman S, Bell R, Fatica M, Lance S: **Outbreak of *Salmonella* Newport infections linked to cucumbers—United States 2014**. *MMWR* 2015, **64**:144-147.

9. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Urbana Infections Linked to Imported Maradol Papayas*. 2017. Available at: https://www.cdc.gov/salmonella/urbana-09-17/index.html [accessed 26.10.17].

10. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Newport and **Salmonella infantis** Infections Linked to Imported Maradol Papayas*. 2017. Available at: https://www.cdc.gov/salmonella/newport-09-17/index.html [accessed 26.10.17].

11. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Anatum Infections Linked to Imported Maradol Papayas*. 2017. Available at: https://www.cdc.gov/salmonella/anatum-9-17/index.html [accessed 26.10.17].

12. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** (**Salmonella** Thompson, **Salmonella** Kiambu, **Salmonella** Agona and **Salmonella** Gaminara) Infections Linked to Imported Maradol Papayas*. 2017. Available at: https://www.cdc.gov/salmonella/kiambu-07-17/index.html [accessed 26.10.17].

13. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Poona Infections Linked to Imported Cucumbers (Final Update)*. 2016. Available at: https://www.cdc.gov/salmonella/poona-09-15/index.html [accessed 26.10.17].

14. Centers for Disease Control and Prevention: *Multistate Outbreak of Listeriosis Linked to Commercially Produced, Prepackaged Caramel Apples Made from Bidart Bros. Apples (final update)*. 2015. Available at: https://www.cdc.gov/listeria/outbreaks/caramel-apples-12-14/index.html [accessed 26.10.17].

15. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Saintpaul Infections Linked to Imported Cucumbers (Final Update)*. 2013. Available at: https://www.cdc.gov/salmonella/saintpaul-04-13/index.html [accessed 26.10.17].

16. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Braenderup Infections Associated with Mangoes (Final Update)*. 2012. Available at: https://www.cdc.gov/salmonella/braenderup-08-12/index.html [accessed 26.10.17].

17. Centers for Disease Control and Prevention: *Multistate Outbreak of **Salmonella** Typhimurium and Salmonella Newport Infections Linked to Cantaloupe (Final Update)*. 2012. Available at: https://www.cdc.gov/salmonella/typhimurium-cantaloupe-08-12/index.html [accessed 26.10.17].

18. Centers for Disease Control and Prevention: *Multistate Outbreak of Listeriosis Linked to Whole Cantaloupes from Jensen Farms, Colorado (Final Update)*. 2012. Available at: https://www.cdc.gov/listeria/outbreaks/cantaloupes-jensen-farms/index.html [accessed 26.10.17].

19. Jackson BR, Salter M, Tarr C, Conrad A, Harvey E, Steinbock L, Saupe A, Sorenson A, Katz L, Stroika S, Jackson KA, Carleton H, Kucerova Z, Melka D, Strain E, Parish M, Mody RK: **Notes from the field: listeriosis associated with stone fruit—United States, 2014**. *MMWR* 2015, **64**:282-283.

20. Public Health Agency of Canada: *Public Health Notice: Outbreak of Salmonella Illness Related to Mangoes*. Health Canada; 2012. https://www.canada.ca/en/public-health/services/food-safety/public-health-notice/public-health-notice-outbreak-salmonella-illness-related-mangoes.html [accessed 26.10.17].

21. Field JP, Belnap J, Breshears DD, Neff JC, Okin GS, Whicker JJ, Painter TH, Ravi S, Reheis MC, Reynolds RR: **The ecology of dust**. *Front Ecol Environ* 2010, **8**:423-430.

22. Ravi S, D'odorico P, Breshears DD, Field JP, Goudie AS, Huxman TE, Li J, Okin GS, Swap RJ, Thomas AD, Van Pelt S: **Aeolian processes and the biosphere**. *Rev Geophys* 2011, **49**.

23. Whicker JJ, Pinder JE, Breshears DD, Eberhart CF: **From dust to dose: effects of forest disturbance on increased inhalation exposure**. *Sci Total Environ* 2006, **368**:519-530.

24. Yamaguchi N, Ichijo T, Sakotani A, Baba T, Nasu M: **Global dispersion of bacterial cells on Asian dust**. *Sci Rep* 2012, **2**.

25. Burkhardt J: **Hygroscopic particles on leaves: nutrients or desiccants?** *Ecol Monogr* 2010, **80**:369-399.

26. •• Berry ED, Wells JE, Bono JL, Woodbury BL, Kalchayanand N, Norman KN, Suslow TV, López-Velasco G, Millner PD: **Effect of proximity to a cattle feedlot on *Escherichia coli* O157:H7 contamination of leafy greens and evaluation of the potential for airborne transmission**. *Appl Environ Microbiol* 2015, **81**:1101-1110.

This study demonstrated that the leafy greens grown in proximity (up to 180 m) of cattle feedlot can become contaminated by *E. coli* O157:H7 indicating that airborne transport of the pathogen can occur. Results suggest that air-mediated dissemination of *E. coli* O157:H7 increased under conditions facilitating the generation of dust.

27. Lawson RJ, Schenker MB, McCurdy SA, Jenkins B, Lischak LA, John W, Scales D: **Exposure to amorphous silica fibers and**

other particulate matter during rice farming operations. *Appl Occup Environ Hyg* 1995, **10**:677-684.

28. Goulter RM, Gentle IR, Dykes GA: **Issues in determining factors influencing bacterial attachment: a review using the attachment of *Escherichia coli* to abiotic surfaces as an example**. *Lett Appl Microbiol* 2009, **49**:1-7.

29. Ong YL, Razatos A, Georgiou G, Sharma MM: **Adhesion forces between *E. coli* bacteria and biomaterial surfaces**. *Langmuir* 1999, **13**:2719-2725.

30. Macarisin D, Patel J, Bauchan G, Giron J: **Effect of spinach cultivar and bacterial adherence factors on survival of *Escherichia coli* O157:H7 on organic spinach leaves**. *J Food Prot* 2013, **76**:1829-1837.

31. Wesche AM, Gurtler JB, Marks BP, Ryser ET: **Stress, sublethal injury, resuscitation, and virulence of bacterial foodborne pathogens**. *J Food Prot* 2009, **72**:1121-1138.

32. Williams AP, Avery LM, Killham K, Jones DL: **Persistence, dissipation, and activity of *Escherichia coli* O157:H7 within sand and seawater environments**. *FEMS Microbiol Ecol* 2007, **60**:24-32.

33. Barak JD, Liang AS: **Role of soil, crop debris, and a plant pathogen in *Salmonella enterica* contamination of tomato plants**. *PLoS ONE* 2008, **27**:e1657.

34. De Roin MA, Foong SC, Dixon PM, Dickson JS: **Survival and recovery of *Listeria monocytogenes* on ready-to-eat meats inoculated with a desiccated and nutritionally depleted dustlike vector**. *J Food Prot* 2003, **66**:962-969.

35. Clausnitzer H, Singer M: **Respirable-dust production from agricultural operations in the Sacramento Valley, California**. *J Environ Qual* 1996, **25**:877-884.

36. Brooks JP, Tanner BD, Josephson KL, Gerba CP, Haas CN, Pepper IL: **A national study on the residential impact of biological aerosols from the land application of biosolids**. *J Appl Microbiol* 2005, **99**:310-322.

37. Brooks JP, Tanner BD, Gerba CP, Haas CN, Pepper IL: **Estimation of bioaerosol risk of infection to residents adjacent to a land applied biosolids site using an empirically derived transport model**. *J Appl Microbiol* 2005, **98**:397-405.

38. Yang Low S, Paez-Rubio T, Baertsch C, Kucharski M, Peccia J: **Off-site exposure to respirable aerosols produced during the disk-incorporation of class B biosolids**. *J Environ Eng* 2007, **133**:987-999.

39. Jones AM, Harrison RM: **The effects of meteorological factors on atmospheric bioaerosol concentrations—a review**. *Sci Total Environ* 2004, **29**:151-180.

40. Jay MT, Cooley M, Carychao D, Wiscomb GW, Sweitzer RA, Crawford-Miksza L, Farrar JA, Lau DK, O'Connell J, Millington A, Asmundson RV: ***Escherichia coli* O157:H7 in feral swine near spinach fields and cattle, central California coast**. *Emerg Infect Dis* 2007, **13**:1908-1911.

41. Bakutis B, Monstviliene E, Januskeviciene G: **Analyses of airborne contamination with bacteria, endotoxins and dust in livestock barns and poultry houses**. *Acta Vet Brno* 2004, **73**:283-289.

42. Okraszewska-Lasica W, Bolton D, Sheridan J, McDowell D: **Airborne *Salmonella* and *Listeria associated* with Irish commercial beef, sheep and pig plants**. *Meat Sci* 2014, **97**:255-261.

43. Miller M, Loneragan G, Harris D, Adams K, Brooks J, Brashears M: **Environmental dust exposure as a factor contributing to an increase in *Escherichia coli* O157 and *Salmonella* populations on cattle hides in feedyards**. *J Food Prot* 2008, **71**:2078-2081.

44. Millner PD: **Bioaerosols associated with animal production operations**. *Bioresour Technol* 2009, **100**:5379-5385.

45. Centers for Disease Control and Prevention: **Update: multistate outbreak of listeriosis**. *MMWR* 1999, **47**:1117-1118.

46. Foong SC, Dickson JS: **Survival and recovery of viable but nonculturable *Listeria monocytogenes* cells in a nutritionally depleted medium**. *J Food Prot* 2004, **67**:1641-1645.

47. Chinivasagam HN, Tran T, Maddock L, Gale A, Blackall PJ: **Mechanically ventilated broiler sheds: a possible source of aerosolized *Salmonella*, *Campylobacter*, and *Escherichia coli***. *Appl Environ Microbiol* 2009, **75**:7417-7425.

48. •• Oni RA, Sharma M, Buchanan RL: **Survival of *Salmonella enterica* in dried turkey manure and persistence on spinach leaves**. *J Food Prot* 2015, **78**:1791-1799.

This study investigated the survival and dispersal of *Salmonella enterica* in dust particles of turkey manure. The results of this study suggest that aerosolized manure particles could be a potential vehicle for Salmonella dispersal to produce.

49. Lues JFR, Theron MM, Venter P, Rasephei MHR: **Microbial composition in bioaerosols of a high-throughput chicken-slaughtering facility**. *Poult Sci* 2007, **86**:142-149.

50. Dev Kumar G, Micallef SA: **Susceptibility of *Salmonella enterica* isolates from tomato farm environments to fatty acids naturally found on tomato fruit**. *Foodborne Pathog Dis* 2017, **14**:293-301.

51. Weese J, Hannon S, Booker C, Gow S, Avery B, Reid-Smith R: **The prevalence of Methicillin-Resistant *Staphylococcus aureus* colonization in feedlot cattle**. *Zoonoses Public Health* 2012, **59**:144-147.

52. Schulz J, Friese A, Klees S, Tenhagen BA, Fetsch A, Rösler U, Hartung J: **Longitudinal study of the contamination of air and of soil surfaces in the vicinity of pig barns by livestock-associated methicillin-resistant *Staphylococcus aureus***. *Appl Environ Microbiol* 2012, **78**:5666-5671.

53. Bicudo JR, Goyal SM: **Pathogens and manure management systems: a review**. *Environ Technol* 2003, **24**:115-130.

54. Venette JR: **How bacteria find their hosts**.*Phytopathogenic Prokaryotes* . 1982:3-30.

55. Guo X, Chen J, Brackett RE, Beuchat LR: **Survival of Salmonellae on and in tomato plants from the time of inoculation at flowering and early stages of fruit development through fruit ripening**. *Appl Environ Microbiol* 2001, **67**:4760-4764.

56. Yashiro E, Spear R, McManus P: **Culture-dependent and culture-independent assessment of bacteria in the apple phyllosphere**. *J Appl Microbiol* 2011, **110**:1284-1296.

57. Han S, Micallef SA: **Environmental metabolomics of the plant surface provides insights on *Salmonella enterica* colonization of tomato**. *Appl Environ Microbiol* 2016, **82**:3131-3142.

58. • Allard SM, Walsh CS, Wallis AE, Ottesen AR, Brown EW, Micallef SA: ***Solanum lycopersicum* (tomato) hosts robust phyllosphere and rhizosphere bacterial communities when grown in soil amended with various organic and synthetic fertilizers**. *Sci Total Environ* 2016, **573**:555-563.

This study assessed the influence of various soil amendments and proximity to farm roads on tomato surface microbiome showing that the air may in fact be a more important reservoir for plant surface microbiota than other agricultural inputs that have been traditional identified as important pathogen sources. The results suggest that dust from passing vehicles may have introduced distinct bacterial taxa to tomatoes planted in rows flanking the road, compared to the interior rows in the field.

59. Duvenage S, Korsten L: **Assessment of foodborne pathogen presence in the peach supply chain and its potential risk to the end consumer**. *Food Control* 2017, **78**:374-382.

60. Feng Y, Li G, Lv X, Xu Y, Wu Q, Shi C, Li Q, Yang B, Wang X, Xi M, Xia X: **Prevalence, distribution, and diversity of *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella* in kiwifruit orchards and processing plants**. *Foodborne Pathog Dis* 2014, **11**:782-879.

61. •• Feng Y, Yang Q, Wang L, Li G, Lv X, Han Q, Liu X, Xia X: **Survey of microbial contamination and characterization of *Escherichia coli* in kiwifruit orchards in Shaanxi, China, 2013**. *Foodborne Pathog Dis* 2015, **12**:857-863.

In this study *Escherichia coli* was recovered from kiwifruits and air samples collected in the same orchards, demonstrating the potential airborne contamination of tree fruits by enteric pathogens.

62. Riordan D, Sapers G, Hankinson T, Magee M, Mattrazzo A, Annous B: **A study of US orchards to identify potential sources of *Escherichia coli* O157:H7**. *J Food Prot* 2001, **64**:1320-1327.

63. Trevors JT: **Viable but non-culturable (VBNC) bacteria: gene expression in planktonic and biofilm cells**. *J Microbiol Methods* 2011, **86**:266-273.