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ANTHRAX IN INDONESIA: A ONE HEALTH APPROACH TO ZOONOTIC THREATS AND INTEGRATED PREVENTION STRATEGIES

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Abstract
Anthrax is a zoonotic disease caused by Bacillus anthracis and remains a significant threat in Indonesia. The disease has a substantial impact on public health, livestock productivity, and economic stability, particularly in areas with traditional farming practices and limited animal health surveillance systems. This study aims to analyze the epidemiology of anthrax in Indonesia using the One Health approach, which integrates human, animal, and environmental health aspects. Data were collected from official government documents, such as the Decree of the Minister of Agriculture of the Republic of Indonesia, as well as scientific literature obtained from reputable databases. The results indicated that approximately 76 % of Indonesia is categorized as suspect areas for anthrax, while 14 % are infected areas, with the highest prevalence in Java, Nusa Tenggara, and Sulawesi. The primary risk factors include the consumption of non-veterinary inspected animal meat, unhygienic handling of carcasses, and the persistence of B. anthracis spores in the environment. Recommended control strategies include periodic livestock vaccination, conducting active surveillance, increasing public awareness, and enhancing the diagnostic laboratory's capacity. The One Health approach has proven effective in reducing the risk of cross-species transmission and improving responses to outbreaks. This study advocates for strengthening the integrated surveillance system, increasing synergy between sectors, and further research on the impact of climate change on zoonotic disease dynamics. With an integrated and collaborative strategy, Indonesia has a significant opportunity to control anthrax sustainably and enhance the resilience of public and animal health.

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Introduction

Anthrax is a zoonotic disease that mainly affects herbivorous animals and can be transmitted to humans [1,2]. The causative agent of the disease is *Bacillus anthracis*, an aerobic Gram-positive bacterium of the genus *Bacillus* [3]. *B. anthracis* is non-motile, spore-forming, and grows optimally at 37 °C in blood or nutrient agar media. This bacterium exhibits two morphological forms during its life cycle: metabolically active vegetative and dormant spore forms. Infections in herbivorous animals typically occur through direct and indirect contact. Meanwhile, transmission of the disease generally occurs in humans through contact with infected animals, animal carcasses, or contaminated animal products [4,5]. *B. anthracis* spores are formed when vegetative cells are exposed to the external environment, mainly through body fluids from infected animal carcasses. These spores are highly resistant to a variety of extreme environmental conditions, including high and low temperatures, chemical disinfectants, desiccation, salting of skin, pH extremes, and irradiation [6,7].

Anthrax is widely recognized for its potential as a biological weapons agent [8]. Historically, the disease has been a significant threat to human health for centuries. Although countries in Asia and Africa are often considered endemic regions, anthrax cases have also been reported in the United States, Australia, Sweden, Italy, and various countries in Europe [3,9,10]. The largest anthrax outbreak was recorded in Zimbabwe, with approximately 10,000 human cases during the period 1978–1980 [8]. Anthrax fatality rates can reach up to 30 %, especially if the skin infection progresses to a systemic form [7]. Globally, an estimated 1.83 billion people (95 % confidence interval: 0.59–4.16 billion) live in areas at high risk of anthrax exposure [11]. In China, a total of 1,244 human anthrax cases were reported between 2018 and 2022 [12]. Overall, anthrax is estimated to affect between 20,000 and 100,000 people per year worldwide [13,14]. More than 1.8 billion people, including more than 60 million farmers and 1.1 billion animals, are also at high risk of the disease [11].

Anthrax is a zoonotic disease that has long been recorded in Indonesia with a history of recurrent endemicity in various regions [15,16]. In Indonesia, human anthrax deaths have been reported in several provinces, especially in endemic areas [17,18]. The first case was reported in 1832 in Kolaka, Southeast Sulawesi, and spread to Lampung (1884) and East Java (1885). Outbreaks returned in 1975–1977 and 1981–1986 in several provinces, including Java, Sulawesi, Nusa Tenggara, and Sumatra. The disease became more widespread in 1988–1994, and the incidence continued to recur until 2020 [19,20]. Data from the Indonesian Ministry of Health recorded fluctuations in cases, with a peak of 77 cases in 2017 in five provinces [21,22]. Major outbreaks occurred again in 2022 in Central Java and Yogyakarta, and recurred in July 2023 and February 2025 in Gunungkidul District [23–26].

Anthrax disease is globally distributed, with the highest incidence reported from endemic regions such as Asia and Africa [26,27]. Vaccination of susceptible animals has proven effective in reducing disease incidence, but implementation remains uneven in many developing countries [28,29]. In the context of global zoonotic threats and the potential use of *Bacillus anthracis* as a biological weapon agent, a comprehensive and cross-sectoral understanding of the dynamics of this disease is required. Therefore, this article aims to take an in-depth look at anthrax disease through a One Health approach, highlighting the interactions between environmental factors, animal, and human health. This review is expected to provide a scientific basis for developing integrated and sustainable prevention and control strategies to minimize the risk of zoonoses in the future.

Objects and methods

This research is a literature review that aims to describe essential aspects of anthrax disease in animals and humans, and how they relate to the One Health approach. Data on the status of anthrax in animals in Indonesia was obtained from official sources, including the Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023 [30]. In addition, relevant scientific articles were accessed online through trusted databases such as PubMed NCBI, DOI, ScienceDirect, and Scopus. Inclusion criteria in this review included articles that discussed the etiology, pathogenesis, epidemiology, diagnosis, clinical manifestations, prevention, and control of anthrax in animals and humans. The collected data were analyzed descriptively to evaluate six main aspects, namely: (1) anthrax etiology and epidemiology, (2) clinical manifestations and diagnosis, (3) control and prevention, (4) One Health approach in anthrax management, (5) socio-economic and environmental implications, and (6) recommendations and future research directions.

Etiology and epidemiology of anthrax

Anthrax is a zoonotic disease caused by *Bacillus anthracis*. This gram-positive, encapsulated bacterium is facultatively anaerobic and can survive in aerobic and anaerobic conditions. The organism can form spores when exposed to the external environment, particularly through the bodily fluids of dead animals, which allows its survival over very long periods [16,31]. The term "*anthrax*" comes from the Greek anthrakites, meaning "like coal", referring to the black eschar that characterizes the skin manifestations of the disease [32]. *B. anthracis* spores survive in soil for up to 40 years [33]. These endospores resist extreme environmental conditions, including desiccation, high and low temperatures, ultraviolet (UV) radiation, gamma rays, and disinfectants [34]. The virulence of *B. anthracis* is mainly determined by two main factors, namely the tripartite toxin and the anti-phagocytosis polypeptide capsule [7]. An overview of the life cycle of *B. anthracis* can be seen in Figure 1.

The genes responsible for the virulence factors of *Bacillus anthracis* are located on two plasmids, pXO1 (182 kb) and pXO2 (95 kb) [35]. The pathogenicity of this organism decreases significantly if one of these plasmids is missing. The tripartite toxin produced consists of three main components: protective antigen (PA), lethal factor (LF), and edema factor (EF). PA's primary function is mediating the entry of LF and EF into target cells, allowing them to interact with critical cellular pathways [36,37]. These toxins are secreted during the vegetative proliferation phase of *B. anthracis* and are responsible for the characteristic symptoms of anthrax [7,38]. Anthrax is recognized as a toxin-mediated disease, with two main toxins, lethal toxin (LT) and edema toxin (ET), acting as virulence factors. LT inhibits immune responses and causes vasomotor instability, while ET induces edema at the cellular and tissue levels.

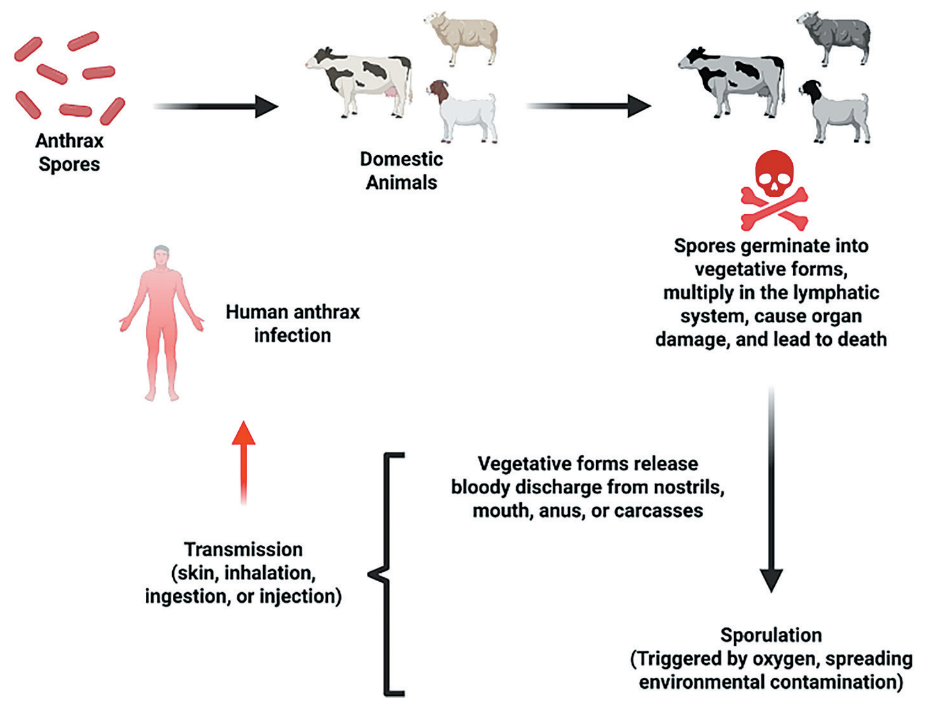

Figure 1. *Bacillus anthracis* transmission cycle in the context of One Health. *B. anthracis* spores infect herbivorous animals through environmental exposure. Infected animals may die suddenly and release spores back into the environment. Humans are infected through direct contact with contaminated animals or animal products. This illustration emphasizes the importance of the One Health approach to anthrax control. The figure was created using BioRender (https://BioRender.com) under a licensed agreement

LT is formed through the interaction between PA and LF, while ET is formed through the interaction between PA and EF [39]. Both plasmids play a crucial role in the virulence of *B. anthracis*. Plasmid pXO1 encodes the anthrax toxin components (PA, LF, and EF), while plasmid pXO2 encodes a polypeptide capsule that protects the bacteria from phagocytosis by the host immune system [40,41]. These genetic products are key to the offensive (toxin) and defensive (capsule) mechanisms of *B. anthracis* and determine the pathogenicity of the bacteria [42]. Thus, losing one of the plasmids, pXO1 or pXO2, will significantly reduce the organism's virulence.

Global warming has the potential to significantly impact the infection dynamics of several pathogenic agents, including anthrax [43]. Increased temperatures have led to the thawing of permafrost, which can release previously trapped *Bacillus anthracis* spores, increasing the risk of human and animal exposure. In addition, global warming also affects the spectrum of disease vectors, altering the development and behavior of various insect and arthropod species, which, although not the primary vectors of anthrax, can still indirectly influence the ecological dynamics of the disease [44]. Rising temperatures and the resulting environmental stress can potentially weaken the immune systems of livestock and wildlife, thereby increasing susceptibility to infections, including anthrax. Anthrax outbreaks tend to occur more frequently and with greater severity in animals stressed by climate change. Global warming also alters the relationship between host and pathogen, creating conditions favoring the persistence and spread of *B. anthracis*. For example, changes in animal population density, migration patterns, and behavior due to climate change may increase the likelihood of previously unexposed animal populations coming into contact with anthrax spores, triggering outbreaks [35,45].

Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023 on the Determination of Animal Disease Situation Status is based on the recommendation of the National Veterinary Authority through epidemiological studies as stated in document Number B-305/HK.100/F4/05/2023 [30]. This decree determines animal disease status in areas classified into: a) Free Area, b) Suspected Area, c) Infected Area, and d) Outbreak Area. The determination of the situation status is based on several parameters, namely: a) disease incidence, b) disease level, c) surveillance system, d) pathogenic nature of the disease, e) disease epidemiology, f) susceptible animal population, and g) geographical location. Figure 2

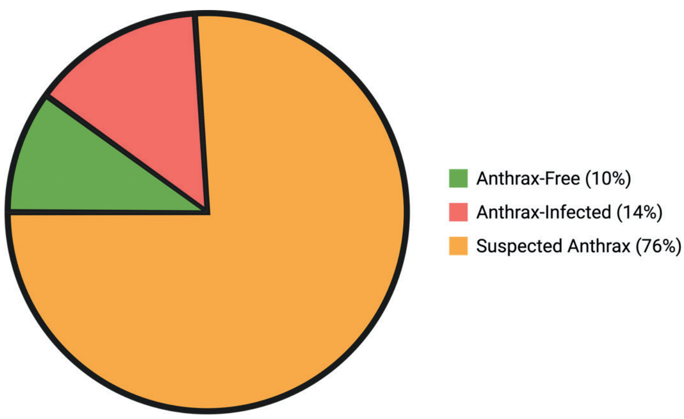

Figure 2. Epidemiological analysis of anthrax disease in Indonesia. The figure was created using BioRender (https://biorender.com) under a licensed agreement, based on the Decree of the Minister of Agriculture of the Republic of Indonesia No. 311/KPTS/PK.320/M/06/2023 [30]

illustrates the epidemiological analysis of anthrax disease in Indonesia. The data shows that approximately 10% of Indonesia is recorded as anthrax-free, reflecting successful disease control and prevention efforts in some regions. On the other hand, around 76% of Indonesia is classified as anthrax suspect areas, indicating a potential risk of disease spread that requires close monitoring and ongoing preventive measures. Meanwhile, around 14% of other regions have been declared as anthrax-infected areas, indicating active infection and the need for further intervention to control the spread of the disease. These findings provide an important insight into the geographical distribution of anthrax disease in Indonesia and emphasize the urgency of strengthening surveillance, biosecurity, vaccination, and rapid response programs to prevent the expansion of cases in suspected and infected areas (Figure 3).

Table 1 shows areas in Indonesia that are free from anthrax. A free area is an area or region where no infectious animal disease agent has ever been found, historically based, or where there was originally a case of a contagious animal disease agent. After observation, it turns out that no more cases of infectious animal disease agents were found [46]. Based on the Decree of the Minister of Agriculture of the Republic of Indonesia No. 311/KPTS/ PK.320/ M/06/2023, several regions in Indonesia have been designated as anthrax-free areas [30]. This status is an essential indicator in zoonotic disease control efforts at the national level through an area-based approach. This designation reflects the successful implementation of strategic infectious animal disease surveillance and prevention programs, including applying One Health principles in these areas. Geographically, anthrax-free regions are primarily in eastern Indonesia. East Nusa Tenggara Province is one of the provinces declared anthrax-free, covering districts/ cities such as Kupang, South Central Timor, North Central Timor, Belu, Alor, Lembata, Rote Ndao, Malacca, and Kupang City. Districts/municipalities recorded as anthrax-free in Papua include Jayapura, Yapen Islands, Biak Numfor, Sarmi, Keerom, Waropen, Supiori, Mamberamo Raya, and Jayapura City. West Papua Province also has a wide coverage of anthrax-free areas, including Fakfak, Kaimana, Teluk Wondama, Teluk Bintuni, Manokwari, South Sorong, Sorong, Raja Ampat, Tambrauw, Maybrat, South Manokwari, Arfak Mountains, and Sorong City. Meanwhile, new administrative regions such as Papua Mountains (Tolikara, Nduga, Lanny Jaya, Central Mamberamo, Yalimo), South Papua (Merauke, Boven Digoel, Mappi, Asmat), and Central Papua (Nabire, Paniai, Puncak Jaya, Mimika, Puncak, Dogiyai, Deiyai, Intan Jaya) have also been designated as anthrax-free areas.

A suspect area is an area or region with a free status of infectious animal disease directly adjacent to an outbreak or infected area, or where a free status or infected status cannot be determined [46]. Table 2 illustrates the situation

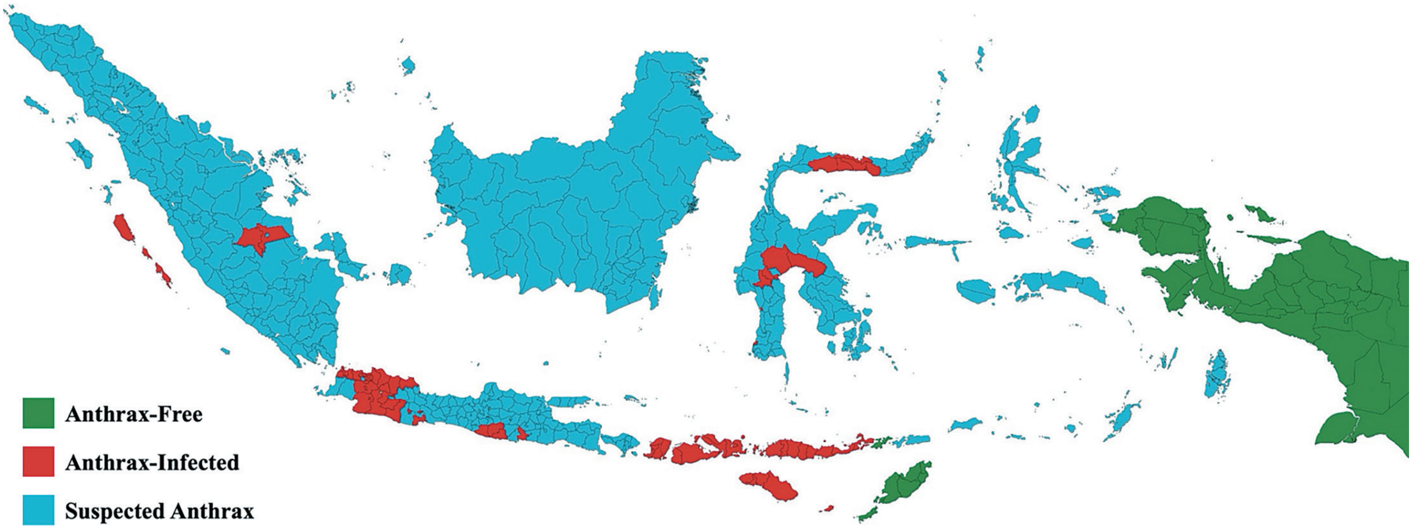

Figure 3. Geographical distribution of anthrax in Indonesia. This figure was created using MapChart.net, based on the Decree of the Minister of Agriculture of the Republic of Indonesia No. 311/KPTS/PK.320/M/06/2023 [30]

Table 1. Situation analysis of anthrax-free areas in Indonesia (Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023 concerning the Determination of Animal Disease Status [30]

Province	District/City	Disease Situation
Nusa Tenggara Timur	Kupang, South Central Timor, North Central Timor, Belu, Alor, Lembata, Rote Ndao, Malacca, Kupang City	Free
Papua	Jayapura, Yapen Islands, Biak Numfor, Sarmi, Keerom, Waropen, Supiori, Greater Mamberaino, Jayapura City	Free
West Papua	Fakfak, Kaimana, Teluk Wondama, Teluk Bintuni, Manokwari, Sorong Selatan, Sorong, Raya Ampat, Tambrauw, Maybrat, South Manokwari, Arfak Mountains, Sorong City	Free
Papua Mountains	Tolikara, Nduga, Lanny Jaya, Central Mamberamo, Yalimo	Free
South Papua	Merauke, Boven Digoel, Mappi, Asmat	Free
Central Papua	Nabire, Paniai, Puncak Jaya, Mimika, Puncak, Dogiyai, Deiyai, Intan Jaya	Free

Table 2. Situation analysis of anthrax suspect areas in Indonesia (Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023 concerning the Determination of Animal Disease Status [30])

Province	District/City	Disease Situation
Aceh	Simeulue, Aceh Singkil, South Aceh, Southeast Aceh, East Aceh, Central Aceh, West Aceh, Aceh Besar, Pidie, Bireuen, North Aceh, Southwest Aceh, Gayo Lues, Aceh Tamiang, Nagan Raya, Aceh Jaya, Bener Meriah, Pidie Jaya, Banda Aceh, Sabang, Langsa, Lhokseumawe, Subulussalam	Suspected
Bali	Jembrana, Tabanan, Badung, Gianyar, Klungkung, Bangli, Karang Asem, Buleleng, Denpasar	Suspected
Banten	Pandeglang, Lebak, South Tangerang	Suspected
Bengkulu	South Bengkulu, Rejang Lebong, North Bengkulu, Kaur, Seluma, Mukomuko, Lebong Kepahiang, Bengkulu Tengah, Bengkulu	Suspected
Daerah Istimewa Yogyakarta	Kulon Progo, Bantul, Sleman, Yogyakarta City	Suspected
DKI Jakarta	Seribu Islands	Suspected
Jambi	Kerinci, Merangin, Sarolangun, East Tanjung Jabung, West Tanjung Jabung, Tebo Bungo, Jambi City, Sungai Penuh	Suspected
West Java	Tasikmalaya, Ciamis, Kuningan, Cirebon, Majalengka, Sumedang, Bandung City, Cimahi City	Suspected
Central Java	Cilacap, Banyumas, Purbalingga, Banjarnegara, Kebumen, Purworejo, Wonosobo, Magelang, Boyolali, Klaten, Sukoharjo, Karanganyar, Sragen, Grobogan, Blora, Rembang, Pati, Kudus, Jepara, Demak, Semarang, Temanggung, Kendal, Batang, Pekalongan, Pemalang, Tegal, Brebes, Magelang City, Surakarta, Salatiga, Semarang City, Pekalongan City, Tegal City	Suspected
East Java	Ponorogo, Trenggalek, Blitar, Kediri, Malang, Lumajang, Jember, Banyuwangi, Bondowoso, Situbondo, Probolinggo, Pasuruan, Sidoarjo, Mojokerto, Jombang, Nganjuk, Madiun, Magetan, Ngawi, Bojonegoro, Tuban, Lamongan, Gresik, Bangkalan, Sampang, Pamekasan, Sumenep, Kediri Cty, Blitar Cty, Malang City, Probolinggo City, Pasuruan City, Mojokerto City, Madiun City, Surabaya, Batu.	Suspected
West Kalimantan	Sambas, Bengkayang, Landak, Mempawah, Sanggau, Ketapang, Sintang, Kapuas Hulu, Sekadau, Melawi, North Kayong, Kubu Raya, Pontianak City, Singkawang	Suspected
South Kalimantan	Tanah Laut, Kotabaru, Banjar, Barito Kuala, Tapin, Hulu Sungai Selatan, Hulu Sungai Tengah, Hulu Sungai Utara, Tabalong, Tanah Bumbu, Balangan, Kota Banjarmasin, Banjar Baru City	Suspected
Central Kalimantan	West Kotawaringin, East Kotawaringin, Kapuas, South Barito, North Barito, Sukamara, Lamandau, Seruyan, Katingan, Pulang Pisau, Gunung Mas, East Barito, Murung Raya, Palangka Raya	Suspected
East Kalimantan	Paser, Kutai Barat, Kutai Kertanegara, Kutai Timur, Berau, Penajam Paser Utara, Mahakam Hulu, Balikpapan, Samarinda, Bontang	Suspected
North Kalimantan	Malinau, Bulungan, Tana Tidung, Nunukan, Tarakan City	Suspected
Bangka Belitung Islands	Bangka, Belitung, Bangka Barat, Central Bangka, South Bangka, East Belitung, Pangkal Pinang	Suspected
Riau Islands	Karimun, Bintan, Natuna, Lingga, Anambas Island, Batam, Tanjung Pinang	Suspected
Lampung	West Lampung, Tanggamus, South Lampung, East Lampung, Central Lampung, North Lampung, Way Kanan, Tulang Bawang, Pesawaran, Pringsewu, Mesuji, West Tulang Bawang, West Pesisir, Bandar Lampung, Metro	Suspected
Maluku	Maluku Southeast West, Southeast Maluku, Central Maluku, Buru, Aru Islands, West Seram, East Seram, Southwest Maluku, South Buru, Ambon City, Tual City	Suspected
North Maluku	West Halmahera, Central Halmahera, Sula Islands, South Halmahera, North Halmahera, East Halmahera, Morotai Island, Taliabu Island, Ternate City, Tidore Islands City	Suspected
Riau	Kuantan Singingi, Indragiri Hulu, Indragiri Hilir, Pelalawari, Siak, Kampar, Rokan Hulu, Bengkalis, Rokan Hilir, Meranti Island, Kota Pekanbaru, Dumai	Suspected
West Sulawesi	Majene, Polewali Mandar, Mamasa, Mamuju, Pasangkayu, Central Mamuju	Suspected
South Sulawesi	Selayar Islands, Bulukumba, Bantaeng, Jeneponto, Takalar, Gowa, Sinjai, Maros, Pangkajene Islands, Barru, Bone, Soppeng, Wajo, Sidenreng Rappang, Pinrang, Enrekang, Luwu	Suspected
Central Sulawesi	Banggai Islands, Banggai, Morowali, Poso, Donggala, Toli Toli, Buol, Parigi Moutong, Tojo Una Una, Sigi, Banggai Laut, North Morowali, Palu City	Suspected
Southeast Sulawesi	Buton, Muna, Konawe, Kolaka, South Konawe, Bombana, Wakatobi, North Kolaka, North Buton, North Konawe, East Kolaka, Konawe Islands, West Muna, Central Buton, South Buton, Kendari City, Baubau City	Suspected
North Sulawesi	Bolaang Mongondow, Minahasa, Sangihe Islands, Talaud Islands, South Minahasa, North Minahasa, North Bolaang Mongondow, Siau Tagulandang Biaro, Southeast Minahasa, South Bolaang Mongondow, East Bolaang Mongondow, Manado City, Bitung City, Tomohon City, Kotamobagu City	Suspected
West Sumatra	Pesisir Selatan, Solok, Sijunjung, Tanah Datar, Padang Pariaman, Agam, Lima Puluh Kota, Pasaran, South Solok, Dharmasraya, Pasaman Barat, Padang, Solok City, Sawah Lunto, Padang Panjang, Bukit Tinggi City, Payakumbuh, Pariaman	Suspected
South Sumatra	Ogan Komering Ulu, Ogan Komering llir, Muara Enim, Lahat, Musi Rawas, Musi Banyuasin, Banyu Asin, South Ogan Komering Ulu, East Ogan Komering Ulu, Ogan Ilir, Empat Lawang, Penukal Abab Lematang llir, North Musi Rawas, Palembang, Prabumulih City, Pagar Alam, Lubuklinggau	Suspected
North Sumatra	Nias, Mandailing Natal, South Tapanuli, Central Tapanuli, North Tapanuli, Toba Samosir, Labuhan Batu, Asahan, Simalungun, Dairi, Karo, Deli Serdang, Langkat, South Nias, Humbang Hasundutan, Pakpak Bharat, Samosir, Serdang Bedagai, Batu Bara, North Padang Lawas, Padang Lawas, South Labuhan Batu, North Labuhan Batu, North Nias, West Nias, Sibolga City, Tanjung Balai, Pematang Siantar, Tebing Tinggi, Medan, Binjai, Padang Sidempuan, Gunungsitoli City	Suspected

of anthrax suspect areas in Indonesia, based on Decree of the Minister of Agriculture of the Republic of Indonesia No. 311/KPTS/PK.320/M/06/2023 [30]. Several areas in Indonesia have been identified as suspect areas. Based on Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023, many districts/cities in various provinces of Indonesia have been classified as anthrax suspect areas [30]. This status indicates the potential presence or risk of spreading *Bacillus anthracis*, either through a history of previous cases, environmental factors that support spore persistence, or limitations in the monitoring and reporting system in the area [30]. The distribution of suspect areas covers almost all provinces in Indonesia, including Sumatra, Java, Kalimantan, Sulawesi, Maluku, and parts of Papua. Densely populated provinces such as East Java, Central Java, and West Java include dozens of districts/cities in the suspect category, raising concerns about the potential impact of zoonoses on public health, the livestock industry, and trade in animals and animal products.

In addition to the central agricultural regions of Java and Sumatra, suspect areas include border areas and islands such as Riau Islands, Bangka Belitung, and North Maluku, which can complicate the response due to limited animal health infrastructure and geographical access. Urban areas such as DKI Jakarta (Thousand Islands) and other major cities are also included in the suspect list, reflecting the possible risk of transmission through the distribution of animals or animal products from different areas. This "suspect" classification does not necessarily indicate an active outbreak, but rather shows the need for increased vigilance, early detection, and strengthening of surveillance systems under the One Health approach. In this context, synergy between the animal health, human health, and environmental sectors is crucial to prevent risk transformation into an outbreak. This status determination provides an essential basis for local and central governments to design strategic policies, including implementing routine vaccination programs, capacity building of veterinary laboratories, and educating communities and farmers on zoonotic risk management. Responsive and collaborative response in these suspected areas will determine Indonesia's success in achieving a national anthrax-free status in the long term.

An infected area is an area or region where cases of certain infectious animal diseases are found in vulnerable animal populations, based on observations [46]. Outbreak areas are areas or regions where cases of certain infectious animal diseases are found in vulnerable animal populations, based on observations [46]. Based on the Decree of the Minister of Agriculture of the Republic of Indonesia No. 311/KPTS/PK.320/M/06/2023, several districts/cities in Indonesia are categorized as anthrax-infected areas, which are areas that have experienced or are currently experiencing confirmed cases of anthrax, both in animals and humans [30]. The distribution of infected areas covers 13 provinces in Indonesia and is spread across major islands such as Java, Sumatra, Sulawesi, and Nusa Tenggara (Figure 3). West Java and East Nusa Tenggara provinces have the highest number of infected districts/cities. West Java includes densely populated areas with high livestock intensity, such as Bogor, Garut, and Bandung, indicating a significant risk of cross-species transmission and unsafe distribution of animal products. On the other hand, East Nusa Tenggara recorded almost the entire mainland of Sumba and Flores as infected areas, indicating that anthrax has become an endemic disease in the region.

Other provinces, such as South Sulawesi (especially Tana Toraja and North Toraja) and DKI Jakarta, are also categorized as infected. Even the entire administrative area of DKI Jakarta is recorded as an infected area, reflecting that even urban areas are not free from anthrax risk, most likely due to the distribution of animals or animal products from infected areas. Areas such as the Mentawai Islands in

Table 3. Situation analysis of anthrax-infected areas in Indonesia (Decree of the Minister of Agriculture of the Republic of Indonesia Number 311/KPTS/PK.320/M/06/2023 concerning the Determination of Animal Disease Status [30])

Province	District/City	Disease Situation
Banten	Tangerang, Serang, Tangerang City, Cilegon City, Serang City	Contracted
Daerah Istimewa yogyakarta	Gunung Kidul	Contracted
DKI Jakarta	South Jakarta, East Jakarta, Central Jakarta, West Jakarta, North Jakarta	Contracted
Gorontalo	Boalemo, Gorontalo, Pohuwato, Bone Bolango, Gorontalo Utara, Gorontalo City	Contracted
Jambi	Batanghari, Muaro Jambi	Contracted
West Java	Bogor, Sukabumi, Cianjur, Bandung, Garut, Indramayu, Subang, Purwakarta, Karawang, Bekasi, Bandung Barat, Pangandaran, Kota Bogor, Kota Sukabumi, Kota Cirebon, Kota Bekasi, Kota Depok, Kota Tasikmalaya, Kota Banjar	Contracted
Central Java	Wonogiri	Contracted
East Java	Pacitan, Tulungagung	Contracted
West Nusa Tenggara	West Lombok, Central Lombok, East Lombok, Sumbawa, Dompu, Bima, West Sumbawa, North Lombok, Mataram, Bima City	Contracted
East Nusa Tenggara	West Sumba, East Sumba, East Flores, Sikka, Ende, Ngada, Manggarai, West Manggarai, Central Sumba, Southwest Sumba, Nagekeo, East Manggarai, Sabu Raijua	Contracted
South Sulawesi	Tana Toraja, North Luwu, East Luwu, North Toraja, Makassar, Pare Pare, Palopo City	Contracted
West Sumatra	Mentawai Islands	Contracted

West Sumatra and Wonogiri in Central Java, although only one district, remain important to monitor as they have the potential to be the starting point for further spread. This geographical distribution emphasizes the urgency of implementing an integrated One Health approach, which combines animal health, public health, and environmental management. This approach should be realized through strengthening active and passive surveillance systems, vaccinating vulnerable animals, closely monitoring the movement of animals and animal products, improving farmer and community education, and cross-sector coordination between health services, livestock services, and local governments. As an archipelago with high inter-regional connectivity, Indonesia's success in controlling anthrax will depend on the ability to implement a collaborative and sustainable risk-based control system.

Anthrax is a severe zoonotic disease that can infect various domestic and wild animal species and, under certain conditions, humans. Its potential to cause large-scale outbreaks, including at a global level, has made it one of the main focuses of veterinary public health and zoonotic disease surveillance systems [3]. Herbivorous animals, especially ruminants, are known to be the main reservoirs of *Bacillus anthracis*, with sheep having higher susceptibility than goats, cattle, and horses. Conversely, some species, such as dwarf pigs and Algerian sheep, show relatively higher levels of resistance to infection [31,47]. As a spore-forming pathogen naturally distributed in the environment, *B. anthracis* is classified as a high-priority threat agent due to its widespread availability in nature, ease of dispersal, and potential to cause significant morbidity and mortality in humans and animals [48]. Anthrax transmission in animals and humans generally occurs through direct contact with infected animals or contaminated animal products, such as meat, blood, skin, or internal organs [12]. Environmental transmission can also occur through inhalation of spores from contaminated soil, while in animals, spores enter mainly through the gastrointestinal tract. In the body, the anthrax bacillus produces a lethal toxin that can cause death, even after treatment with antibiotics [16].

Anthrax can manifest in several clinical forms depending on the route of infection, namely cutaneous, gastrointestinal, and inhalation anthrax [12]. Cutaneous anthrax is the most common form, occurring through direct contact with spores through skin wounds, and is characterized by characteristic lesions of black eschar; the mortality rate is relatively low (~5 %) if appropriately treated [7,49]. Gastrointestinal anthrax results from ingestion of spore-contaminated food and can cause severe symptoms such as abdominal pain, bloody diarrhea, and shock, with a mortality of around 50 % [7,50]. Inhalational anthrax, caused by spore inhalation, is the most fatal form, causing hemorrhagic mediastinitis and pulmonary edema; without immediate treatment, the mortality rate approaches 100 % [49]. Other variants, such as injectional anthrax and welder's anthrax, have been reported in certain at-risk groups, expanding the clinical spectrum and routes of transmission of the disease [32,51].

Human infection is generally a consequence of animal outbreaks and is often associated with the slaughter or consumption of sick animals, especially in regions with low food security, weak animal health surveillance systems or inadequate vaccination coverage, and can occur through inhalation of anthrax spores [11,52,53]. Of these three forms, cutaneous anthrax is the most common and accounts for more than 95 % of human cases [12]. Clinical manifestations are localized skin lesions on areas of the body that have frequent direct contact with animals or animal materials, such as the face, neck, hands, and arms [54]. Studies in Bangladesh have consistently shown that the risk of anthrax transmission to humans is highly correlated with slaughtering practices of infected animals and consumption of unhygienically processed animal products, including raw meat, blood, skin and internal organs [55–57]. Although most cases of natural anthrax are limited to the non-systemic cutaneous form, the infection can progress to systemic if not treated appropriately, especially when entered through an open wound on the skin [28,29].

Clinical manifestations and diagnosis

Diagnosis of anthrax in animals generally begins with observation of typical clinical symptoms, such as elevated body temperature, depression, respiratory distress, bloody discharge from the body orifices, tremors, and sudden death within a few hours of the onset of initial symptoms. To confirm anthrax cases, field disease investigation laboratories (FDILs) and veterinary hospitals in endemic areas usually use the polychrome methylene blue (PMB) staining technique, known as the McFadyean reaction, as the basic diagnostic method [58,59]. In addition to these conventional methods, more sophisticated molecular-based diagnostic techniques have been applied, such as polymerase chain reaction (PCR), which allows for rapid and accurate detection of target DNA [60]. In some cases, more sophisticated molecular approaches such as multilocus variable number tandem repeat analysis (MLVA) are also used for epidemiological analysis and genetic characterization of bacterial isolates from suspected infected animal samples [61].

In humans, clinical symptoms of anthrax generally begin with the appearance of painless skin lesions, which may take the form of papules or vesicles, and progress to solid black colored eschar. This manifestation is often considered an early indication or tentative case of cutaneous anthrax. To confirm the diagnosis, swab samples are taken from the exudate of the skin lesions and then analyzed using various diagnostic methods. The techniques used range from conventional methods such as Gram stain and Loeffler's methylene blue stain to advanced molecular approaches such as polymerase chain reaction (PCR) and multilocus variable-number tandem repeat analysis (MLVA) [55,57]. Each diagnostic method has varying sensitivity levels (Se) and specificity (Sp), requiring different laboratory infrastructure and technology. In resource-limited settings, diagnosis generally relies on clinical manifestations and basic microbiological techniques, including bacterial culture. However, in countries with more advanced laboratory facilities, competence has been developed to perform molecular-based detection and more specific microbial cultures to identify and confirm the presence of *Bacillus anthracis* in human clinical samples [61,62,63].

Anthrax control and prevention

Anthrax control requires a multidisciplinary approach that includes medical interventions, animal health policies, environmental surveillance, and active community involvement. Various strategies have proven effective in suppressing the spread of the disease, including timely reporting and monitoring of cases, rapid response to extraordinary events, restricting the movement of animals and animal products from affected areas, and managing animal carcasses through safe burning or burial methods. Routine disinfection of livestock facilities and vaccination of at-risk animals are also key components of control strategies [12,51].

Live attenuated anthrax vaccines have been widely used and shown to provide adequate protection. However, they still have limitations, including residual toxicity, relatively short duration of protection, and reports of post-vaccination mortality [64,65]. Therefore, developing a new generation of safer vaccines that provide long-term immunity is urgently needed, utilizing advances in recombinant vaccine technology and adjuvants. In addition, the high mortality rate in gastrointestinal and inhalation anthrax is due to toxin production by *Bacillus anthracis* and the limited effectiveness of conventional therapies. The development of therapies targeting the toxin is a top priority in improving survival rates [51]. Currently, antimicrobial therapy remains the mainstay of anthrax treatment. However, adjuvant therapies in the form of antitoxins have been developed and approved by the Food and Drug Administration (FDA), including Anthrax Immune Globulin Intravenous (AIGIV/Anthrasil), raxibacumab (Abthrax), and obiltoxaximab (Anthim). These three agents work by binding to protective antigen (PA) and inhibiting the formation of lethal toxin (LT) and edema toxin (ET) [48]. In addition to therapy, raxibacumab and obiltoxaximab can be used as post-exposure prophylaxis (PEP). The Centers for Disease Control and Prevention (CDC) recommends the use of antitoxins as adjunctive therapy for systemic anthrax cases, with no restrictions on age or risk group [66–68].

Non-medical aspects also play an important role in anthrax prevention and control. Continuous education of the public, especially farmers and field workers, is crucial in increasing risk awareness and preventing panic during an outbreak. Public education can be done with a comprehensive campaign about anthrax, its transmission symptoms, and preventive measures [6,10]. The media, farmer communities, animal trader communities, government, and other relevant institutions are key actors in the efficiency and effectiveness of anthrax mitigation in Indonesia [69,70]. This is important so that anthrax does not become a prolonged public threat [71,72].

Community education is becoming increasingly important as collective behavior and culture change [73,74]. Such efforts require a consistent and coordinated cross-sectoral approach, manifested by implementing Behavior Change Programs based on the Information, Education, and Communication/Behavior Change Communication (IEC/BCC) approach. However, some of these efforts are insufficient if not accompanied by direct intervention against the transmission source. Unfortunately, the current vaccination coverage of livestock against anthrax is still not optimal. Therefore, we recommend maximum annual vaccination of livestock, especially cattle. Routine vaccination significantly mitigates and reduces anthrax incidence [10,62].

To achieve effective herd immunity, at least 80 % of the cattle population in an area should receive annual vaccination [24]. To enable rapid response, cross-sector coordination between health, livestock, and forestry services must be strengthened, especially in reporting suspicious animal deaths. An active surveillance system and daily reporting by veterinary services should be implemented to detect disease early and prevent its spread. In addition, human resource capacity building through regular training for health workers and veterinarians is important in preparedness for zoonoses such as anthrax. Furthermore, anthrax is also categorized as a potential threat in bioterrorism, given that the pathogen is highly lethal and *B. anthracis* spores can survive in the environment for long periods. Therefore, national preparedness should be enhanced through the provision of isolation facilities, development of reliable diagnostic reagents, and stockpiling of vaccines and antibiotics as part of an emergency response to a possible bioterror attack [51,75].

One Health: an integrated approach to anthrax management

Prevention and control of zoonotic diseases, including anthrax, requires close coordination between the human health, animal health, and environmental management sectors. The One Health approach is a strategic framework that emphasizes the close linkages between these three components in global health [76]. The basic principles of One Health include cross-sector collaboration, integration of surveillance systems, and synergy in implementing public and animal health programs. One Health implementation enables early detection and rapid response to potential outbreaks through efficient and effective data-driven information exchange [77]. Furthermore, One Health encourages the development of integrated policies that consider shared risks such as socio-economic and ecological factors that influence zoonotic disease spread at local, national, and global levels [6].

Implementing the One Health approach includes important activities such as two-way communication between sectors, exchange of epidemiological surveillance data, use of shared diagnostic tools, and adoption of best practices in zoonosis control. These efforts have supported accurately depicting the endemic situation, early detection of extraordinary events, rapid response to outbreaks, and implementation of vaccination programs in high-risk areas [78,79]. Furthermore, strengthening local capacity, improving access to treatment in endemic areas, and interdisciplinary research initiatives play an important role in strengthening the effectiveness of anthrax control. Outbreaks and pandemics in recent decades have exposed the weaknesses of the global health system, especially in dealing with diseases that involve complex interactions between humans, animals, plants, and the environment. This emphasizes the importance of One Health as a collaborative, cross-sectoral, integrative, and holistic framework [80].

The One Health approach also addresses the limitations of conventional sectoral and fragmented approaches. By emphasizing the importance of integrated management of zoonotic risk factors, it supports capacity building of cross-species surveillance systems. It identifies critical points of human-animal-environment interaction within a syndemic framework. The approach allows for more efficient and risk-based intervention strategies. Case studies from several countries show the successful application of the One Health approach in anthrax control, especially in areas with endemic status [4,6,27]. Strategies include inter-agency collaboration, mass vaccination of animals and humans, development of an integrated surveillance system, improvement of health infrastructure, and evaluation of public knowledge and perception. In addition, developing technical guidelines and operational protocols is an important component in supporting sustainable disease management [81–83].

In Indonesia, One Health implementation faces various challenges, including public knowledge, stakeholder knowledge, governance and policy, social and cultural factors, limited cross-sector coordination, low livestock vaccination coverage, and limited diagnostic laboratory capacity in the regions [54,84,85]. However, opportunities for integrating these approaches remain wide open, particularly through strengthening national policies, developing integrated information systems, and interprofessional training. With adequate regulatory support and strong political commitment, the One Health approach has great potential to be adopted as the primary strategy in managing priority zoonoses, including anthrax, in Indonesia.

Socio-economic and environmental implications

Anthrax not only impacts public health, but also has far-reaching consequences on social, economic, and environmental aspects. In the livestock sector, anthrax outbreaks often lead to mass livestock deaths that have a direct impact on farmers' income, food security, and economic stability, especially in rural areas that rely heavily on the agricultural sector. In addition to losses due to livestock deaths or due to livestock reduction, restrictions on the mobility of animals and animal products during outbreaks also disrupt local and regional trade [18]. Farmers must incur additional costs for outbreak control, such as emergency vaccination, environmental disinfection, and compensation for losses. Long-term anthrax disruption can weaken the country's agricultural supply chain [3].

From a social perspective, the emergence of an anthrax case can create fear in the community and stigmatize affected individuals or communities [69,77]. This could exacerbate the marginalization of vulnerable groups and hinder the effectiveness of public health interventions. In some cases, excessive fear has led to the rejection of health workers or volunteers, creating barriers to vaccination and open reporting of cases. Socially, anthrax cases also have the potential to undermine social cohesion, which should be an asset in building community wellbeing [86].

Anthrax also impacts resource use efficiency and livestock productivity [87]. In most developing countries, vaccination programs in susceptible animals in enzootic areas have reduced disease prevalence to relatively low levels nationwide. However, significant losses can still occur in specific population groups [3]. These losses include post-vaccination animal mortality, reduced livestock production, destruction of infected carcasses and by-products, and temporary closure of abattoirs [88]. Anthrax fatality rates vary between animal species [89]. Pigs generally have a high cure rate, whereas clinical infections in ruminants and horses tend to result in death [90]. Despite relatively low mortality rates in carnivores, information on infection rates in wildlife is limited [91].

The environment is a crucial element in the epidemiological dynamics of anthrax, especially given the ability of *Bacillus anthracis* to form highly resistant spores that can persist in soil for many years. Global climate change, land degradation, and the increasing frequency of extreme climate events such as floods and droughts have accelerated the distribution of infectious diseases, including anthrax, through their effects on microbial ecosystems and wildlife habitats [92]. Complex interactions between climatic factors, environmental management practices, and human activities such as wildlife consumption and trade increase the risk of zoonotic pathogens emerging and spreading across regions [93].

Studies show that soil characteristics play an important role in the persistence of anthrax spores. Endemic areas with clay or loam soils containing high calcium and organic carbon are known to be highly conducive to spore survival. High temperatures, extreme rainfall, and acidic soil pH also increase the potential for environmental contamination [57]. Research by Vieira et al. [62] found that 77.08% of clay and 22.92% of loam samples from endemic areas contained anthrax spores, with an average pH of 6.38. Clay soils were noted to be more than three times more likely to be contaminated with spores than non-clay soils. Inadequate carcass management practices, such as burial without disinfection or spore removal, exacerbate this persistence. Such practices create hotspots of infection for wild animals and livestock grazing in contaminated areas [63]. Therefore, waste and carcass management strategies, including sterilization of contaminated materials and decontamination of outbreak sites, are crucial steps in breaking the transmission cycle.

Socio-cultural aspects also have a significant influence on the dynamics of anthrax transmission. In some remote communities, the practice of consuming the meat or blood of animals that die suddenly persists and is a significant route of infection [83,94]. Low community knowledge of the risk of anthrax, limited access to health services and veterinarians, and reluctance to accept modern medicine further exacerbate the situation [10,95,96]. In the context of global environmental change, future One Health approaches should be able to integrate climate projections and ecological risks in health system planning. Cross-disciplinary collaboration between climatologists, ecologists, and health experts is needed to design adaptive strategies to mitigate the emergence of new pathogens and re-emerging diseases. Integrating climate data, animal habitat maps, and zoonotic surveillance information is important in realizing a resilient and sustainable early warning system.

Recommendations and future research directions

Effective anthrax control requires a multisectoral strategy integrating human, animal, and environmental dimensions within the One Health framework. Addressing zoonoses' complex and dynamic risk factors requires a holistic approach that includes improving surveillance, diagnostic innovation, strengthening human resource capacity, and empowering local communities. One of the top priorities is developing an integrated surveillance system that combines data from the human, animal, and environmental health sectors. This surveillance should be participatory and community-based, especially in endemic areas with limited infrastructure. Early reporting by farmers and local communities can be an effective detection tool, but this requires support in the form of technical training and reporting incentives. Significant barriers remain in diagnosis, especially in rural areas without basic laboratory facilities. Therefore, providing simple diagnostic tools such as Gram stain and polychrome methylene blue (PMB) tests and training field laboratory technicians should be an integral part of surveillance strengthening programs [57].

Diagnostic innovations and community-based interventions are also urgent. Molecular-based rapid diagnostics and cheap and easy-to-use point-of-care testing methods must be developed to detect anthrax cases accurately at the point of source. On the other hand, digital technology, such as mobile app-based reporting systems, can also be utilized to accelerate case tracking and risk area mapping. Community involvement in disease education and control through social and behavior change communication (SBCC) campaigns will increase risk awareness and strengthen compliance with veterinary health protocols [57].

Capacity building of health workers across sectors is the primary foundation for implementing the One Health approach. Medical personnel, veterinary paramedics, and environmental officers must receive continuous training on anthrax detection, handling, and mitigation, including safe waste and carcass management. Authorized veterinarians must handle infected animals according to protocols. Meanwhile, the community needs to be equipped with practical information on safe management of livestock and foodstuffs and instill a responsive and responsible attitude. The community needs to receive guidance regarding the direct application of various practices in daily life.

Empowering animal health cadres and extension workers is crucial in bridging the information between authorities and grassroots communities. Strategically, policy and funding support from the government is needed, especially in providing door-to-door vaccination services, surveillance of meat and animal products during the outbreak season, and compensation for affected farmers. Strict inspection of animal products entering rural markets will help reduce human cases of cutaneous anthrax [59]. Future research directions need to focus on the development of climate-based and geospatial prediction models to identify new anthrax hotspots; evaluation of the effectiveness of One Health approaches in local and multicultural contexts; innovation of vaccines that are more durable and easier to distribute, especially for remote areas; and socio-cultural research related to risk perception, trust in health services, and local practices in livestock and carcass management. With an evidence-based approach and consistent cross-sector collaboration, anthrax control can be implemented more effectively and sustainably, while strengthening the resilience of public health systems at the local and national levels.

Conclusion

Anthrax is a serious zoonotic threat in Indonesia that requires an integrated and cross-sectoral approach. The study results show that around 76% of Indonesia is classified as suspected infected areas, while 14% have been confirmed infected, mainly in Java, Nusa Tenggara, and Sulawesi. Key risk factors include unhygienic farming practices, consumption of contaminated animal products, and the ability of *Bacillus anthracis* spores to persist in the environment. The One Health approach, which integrates human, animal, and environmental health aspects, has proven effective in controlling this disease. The study recommends strengthening integrated surveillance systems, increasing livestock vaccination coverage, and evidence-based public education. In addition, further research is needed to develop adaptive strategies to deal with disease dynamics due to climate change. The One Health approach is seen as increasingly relevant in dealing with zoonotic threats in the era of globalization, with great potential to strengthen the resilience of public health systems and livestock sustainably.

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