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Review

Advanced Strategies for Mitigating Particulate Matter Generations in Poultry Houses

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Abstract: Poultry farming plays a key role in agricultural air emissions. Particulate matter (PM) level tends to be high in broiler and cage-free layer houses, that may impair health and welfare of animals and their caretakers. To protect public health and welfare, the occupational exposure limit for PM_{10} and $PM_{2.5}$ (i.e., PM diameters that are generally $\leq$10 and 2.5 µm, respectively) are suggested not to exceed 150 µg m^{-3} and 35 µg m^{-3}, respectively, based on 24-h concentrations thresholds as suggested by US. EPA. However, the levels of PM_{10} and $PM_{2.5}$ in poultry houses could be 100 times higher than that limit. For instance, PM_{10} and $PM_{2.5}$ levels in cage-free henhouses are higher than 15,000 µg/m^3 and 3500 µg/m^3 in wintertime. Therefore, it is critical to identify the primary factors affecting PM generation in poultry houses and apply corresponding mitigation strategies. This review paper summarizes PM emission factors, mitigating strategies, and impacts on birds' and caretakers' health, and welfare. Generally, PM emissions are affected by various factors, including housing types, seasonal and diurnal variation, manure management, bedding materials, ventilation rates, and birds' activities. High PM concentrations in poultry houses impair birds' and caretakers' liver, kidneys, and respiratory systems. Thus, different mitigating strategies are discussed in this study for addressing those issues. Effective mitigation strategies include frequent house cleaning, optimum light intensity, liquid spraying, bedding management, and air filtration systems. However, mitigation strategies can be cost-prohibitive and have side effects. Therefore, poultry farms should select mitigation strategies based on farm location, climate conditions, environmental policies, and available resources (government assistance programs).

Keywords: poultry production; air quality; dust; mitigating strategies; animal health and welfare

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1. Introduction

Animal feeding operations (AFOs) are important sources of air pollutant emissions into the environment [1–5]. The primary air emissions include particulate matter (PM) and other gases like greenhouse gases and ammonia (NH_3), as these gases pose a high potential risk to air quality, public and animal health, and climate change [6–12]. Among these air pollutants, PM is considered one of the harmful air pollutants within and outside of animal houses because of its composition and emission rates at the animal and local levels [6]. According to the WHO (World Health Organization), the fine PM such as $PM_{2.5}$ (inhalable particles with diameters $\leq$2.5 micrometers) causes 4.2 million premature deaths worldwide per year [11]. Moreover, the fine PM generated in the environment is the main source of haze in some parts of the United States [12–14]. In addition, depending on dust composition, settling down may cause lakes or streams to be acidic, reduce soil nutrients, and contribute to acid rain formation [12]. According to the European Environmental Agency, poultry and pig housings contributed approximately 50% and 30% of $PM_{2.5}$ (PM with aerodynamic diameter $\leq$2.5 µm) and 57% and 32% of PM_{10} (PM with aerodynamic diameter $\leq$10 µm) emissions, respectively [15].

Particulate matters in confined animal housing are heterogeneous combinations of biologically generated materials and aerosolized pollutants such as feed additives, broken feather pieces, dried NH_3, viable and nonviable bacteria, endotoxins, glucans, molds, and fungal spores [16–18]. In poultry houses, the primary sources of PM include feathers, feeds, urine mineral crystals, manure, and bedding materials. The PM generated from these sources shows harmful effects on the health of animals and caretakers [19,20]. For example, in birds, higher PM levels result in an increased risk of chronic bronchitis, cardiovascular illness, pneumonia lesions, asthma-like symptoms, and lung cancer [21,22], while in caretakers, it causes bronchitis, asthma, and organic dust toxic syndrome [20]. In addition, poultry farm workers are usually at high risk of occupationally being exposed to many respiratory problems leading to higher asthma rates or other respiratory symptoms at work [23].

This review study aims to discuss various factors that affect PM emissions and potential strategies to reduce its generation from poultry production systems. Therefore, the primary objectives of this study were to (1) summarize factors that affect PM or dust levels in poultry houses, (2) analyze potential strategies for mitigating PM generations, and (3) discuss the pros and cons of different methods and expectations on new strategies to improve air quality and health and welfare of animals and their caretakers.

2. Dust Composition and Mixture

Particulate matter composition varies according to animals and livestock housing [24]. In poultry housing, PM is entirely biological, organic, and inorganic in its origin (Figure 1), which typically consists of a complex mixture of solid and liquid materials such as bedding materials, feathers, feeds, skin, excreta, dander, and microorganism (Table 1). Particulate matter from poultry houses constitutes about 90% organic content [25]. Dander, excreta, feathers, feed, litter material, bacteria, and skin are all examples of organic PM [16–18], while inorganic PM is usually the consequence of secondary interactions between NH_3 and acidic gases, which contribute to the fine PM fraction [26]. Based on particle sizes, feather-releasing airborne PM contributes about 4% to 43% fine PM and 6% to 35% coarse PM, while manure contributes ranges from 9–85% fine and 30–94% coarse PM [17]. Similarly, based on particle mass, feathers contribute about 17–68% in fine and 4–49% in coarse PM, while manure contributes 6–77% fine and 31–96% in coarse PM. In addition, in the case of poultry houses, PM could be rich in nitrogen content. According to Cambra-Lopez et al. (2010), elemental analysis of PM in poultry houses consists of N, O, C, S, P, Ca, Na, K, and Mg from feedstuffs, feces, and skin [21]. In addition, within PM, many pathogenic and nonpathogenic microorganisms are found attached to the surface [27].

Figure 1. Poultry dust obtained from the exhaust fan of the cage-free laying hen house at the UGA research facility.

In broiler housing, the primary sources of PM are down feathers, mineral crystals from urine, and litter, whereas the most prominent sources of waste in layer barns are skin, feathers, excrement, urine, feed, and litter [25]. Based on particle size, PM is classified into PM_1 (PM with aerodynamic diameter $\leq$1 µm), $PM_{2.5}$ (PM with aerodynamic diameter $\leq$2.5 µm), PM_4 (PM with aerodynamic diameter $\leq$4 µm), PM_{10} (PM with aerodynamic diameter $\leq$10 µm), and total suspended particle (TSP, PM with aerodynamic diameter $\leq$100 µm) [24,28,29]. The size of $PM_{2.5}$ is 30 times smaller than the size of the average human hair [14]. The emission rate of PM_{10} was directly influenced by the activity of the hens, ambient temperature, and ventilation rate [30]. It has been found that a significant portion of the NH_3 released contributes to the burden of $PM_{2.5}$ [31,32].

Table 1. Particulate matter composition varies with different housing systems.

Sources	PM Type	PM Constitute	References
Broilers	TSP	Feathers, skin, bacteria, fungus, fecal matter, spilled feed, mold spores, and bedding fragments	[16]
Broilers	$PM_{2.5}$ PM_{10}	72.1% manure, 21.3% feathers, 5.8% wood shaving, and 0.7% ambient PM 95.6% manure and 4.4% feathers	
Layers	$PM_{2.5}$ PM_{10}	63.7% manure and 36.3% feathers 69.6% manure, 30.0% feathers, and 0.4% ambient PM	[17]
Layers	$PM_{2.5}$ PM_{10}	54.2% manure, 23.2% feed, 17.0% feathers, and 5.5% ambient PM 85.5% manure and 14.5% feathers	
Turkey	$PM_{2.5}$ PM_{10}	39.1% feathers, 34.8% manure, 26.1% wood shavings, and 0.1% ambient PM 51.9% manure, 25.1% feathers, and 22.9% wood shavings	
Broilers	TSP	50% excreta, 30% litter, 15% feed, and 5% feathers	[18]
Poultry	TSP	90% organic composition like a feather, feeds, urine mineral crystal, manure, and bedding materials	[25]
Poultry	TSP	Organic and inorganic particles: excreta, feathers, mites, dander, bacteria, fungi, fungal spores, and endotoxins	[33]
Poultry	TSP	Bedding materials and floor	[34]
Poultry	TSP	Feed, excreta, hair, and dander	[35]

3. Factors Affecting Dust Generations

Dust emissions from poultry farms are affected by various factors and changes according to variable climatic conditions, applied management practices, the number of birds, and housing types. Various researchers have explained many factors that cause PM emission, as shown in Figure 2 [9,24,36–39].

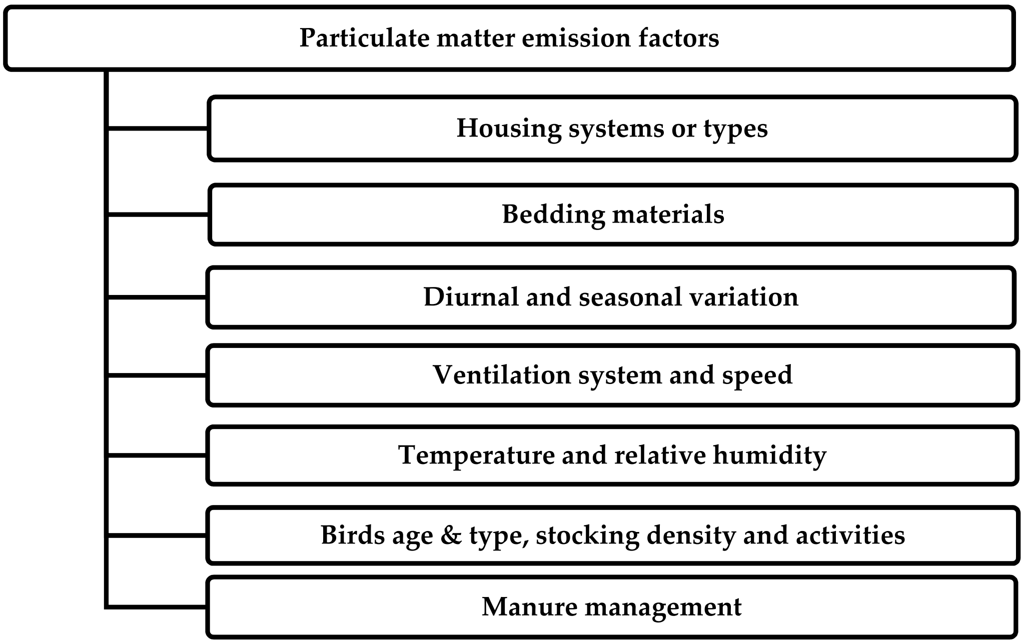

Figure 2. Factors affecting PM emissions in poultry housing.

3.1. Effect of Housing Systems on PM

Poultry housing is the major source of PM emissions. Different housing systems (e.g., floor-raised, aviary, conventional caged, and enriched colony) show different PM emissions and concentrations. Among different housing types, the cage-free (CF) housing (aviary) system resulted in significantly higher PM concentrations and emissions [40]. The daily mean PM_{10} level in CF housing was about six to nine times higher than the conventional cage (CC) and the enriched colony housing (EC) systems [3]. Therefore, emission mitigation studies should consider CF housing systems as the priority. In addition, CF shows higher concentrations of airborne bacterial concentrations and emissions rates than CC and EC houses because PM is the primary carrier of airborne bacteria. In addition, house types can be divided into high-raised (HR) or manure belts (MB). According to Chai et al. (2012), the HR houses had higher NH_3 concentrations but lower CO_2, H_2S, and PM_{10} concentrations than the MB house [9]. The detail of PM concentration and emissions in different houses is detailed in Table 2.

Table 2. Particulate matter emissions and concentration of different PM sizes in various poultry housing systems.

Housing System	Location	Bird Density	Monitoring Device	PM Size	PM Emission (g $day^{-1}AU^{-1}$)	PM Concentration ($mg\ m^{-3}$)	References
CC	Midwest, US	200,000	TEOMs	$PM_{2.5}$ PM_{10}	N/A	0.04 0.59	[3]
CC	Midwest, US	200,000	TEOMs	$PM_{2.5}$ PM_{10}	0.9 * 15.7 *	N/A	[40]
CC	France	45,257 ± 18,800	Stationary captor	$PM_{2.5}$	N/A	0.11	[41]
CC	Germany	1350	Glass fiber filter	TSP	N/A	0.6 1.25	[42]
Caged layer	South Korea	5636	Gravimetric method and air sampling pump	TSP	N/A	3.66 1.99	[43]
Caged hen	UK	N/A	TEOMs, Micro Orifice Uniform Deposit Impactors	$PM_{2.5}$ PM_{10}	6.9 * 16.9 *	N/A	[44]

Table 2. *Cont.*

Housing System	Location	Bird Density	Monitoring Device	PM Size	PM Emission (g $day^{-1}AU^{-1}$)	PM Concentration ($mg\ m^{-3}$)	References
Furnished cages	Sweden	7500	Battery powered pump	TSP	N/A	2.3	[45]
Battery caged	Toledo, Spain	100,000	TEOMs	$PM_{2.5}$ PM_{10}	N/A	0.55 ± 0.38	[46]
EC	Midwest, US	50,000	TEOMs	$PM_{2.5}$ PM_{10}	1.7 * 15.6 *	N/A	[40]
EC	Midwest, US	50,000	TEOMs	$PM_{2.5}$ PM_{10}	N/A	0.41 3.95	[3]
EC	Toledo, Spain	100,000	TEOMs	$PM_{2.5}$ PM_{10}	N/A	0.024 ± 0.025	[46]
EC	Germany	1500	Glass fiber filter	$PM_{2.5}$ PM_{10}	N/A	0.5 1.95	[42]
EC	France	45,257 ± 18,800	Stationary captor	$PM_{2.5}$	N/A	0.15	[41]
CF	Beijing, China	1800	Arduino Mega2560 microcontroller, DFRobot sensor shield	$PM_{2.5}$ PM_{10} TSP	N/A	0.04 ± 0.03 0.42 ± 0.10 1.92 ± 1.91	[47]
CF	Midwest, US	50,000	TEOMs	$PM_{2.5}$ PM_{10}	8.8 * 100.3 *	N/A	[40]
CF	Midwest, US	50,000	TEOMs	$PM_{2.5}$ PM_{10}	N/A	0.14 3.95	[3]
CF	France	20,750 ± 10,250	Stationary captor	$PM_{2.5}$	N/A	1.19	[41]
CF	IOWA, USA	50,000	TEOMs	PM_{10} $PM_{2.5}$	29.5 ± 11 2.1 ± 1.7	2.30 ± 1.60 0.25 ± 0.26	[48]
CF	Netherlands	35,000 and 24,712	Virtual cascade impactors, DustTrack aerosol monitor	PM_{10}	N/A	3.06 ± 1.54	[17]
CF	Germany	2300	Glass fiber filter	$PM_{2.5}$ PM_{10}	N/A	2.3 5.4	[42]
FR	France	40,780 ± 16,804	Stationary captor	$PM_{2.5}$	N/A	0.37	[41]
FR broiler	UK	N/A	TEOMs, Micro Orifice Uniform Deposit Impactors	$PM_{2.5}$ PM_{10}	N/A	0.66 2.99	[44]
FR	Sweden	6900	Battery powered pump	TSP	N/A	12	[45]
FR	Netherlands	16,500 and 3850	Virtual cascade impactors, DustTrack aerosol monitor	PM_{10}	N/A	3.94 ± 0.69	[17]
Broiler	Netherlands	50,400 and 2675	Virtual cascade impactors, DustTrack aerosol monitor	PM_{10}	N/A	1.96 ± 0.55	[17]
Broiler	South Korea	5636	Gravimetric method and air sampling pump	TSP	N/A	5.08 2.75	[43]
Broilers	UK	N/A	TEOMs, Micro Orifice Uniform Deposit Impactors	$PM_{2.5}$ PM_{10}	5.1 31.6 *	N/A	[44]
Free-range hen	UK	N/A	TEOMs, Micro Orifice Uniform Deposit Impactors	$PM_{2.5}$ PM_{10}	36.4 * 139 *	N/A	[44]

Table 2. *Cont.*

Housing System	Location	Bird Density	Monitoring Device	PM Size	PM Emission (g $day^{-1}AU^{-1}$)	PM Concentration (mg m^{-3})	References
Turkey	Netherlands	5000 and 4040	Virtual cascade impactors, DustTrack aerosol monitor	PM_{10}	N/A	2.32 ± 0.99	[17]
Two Commercial laying hen	Ontario, CA	65,000 70,000	DustTrak aerosol analyzers	PM_{10} $PM_{2.5}$	2.55 ± 2.10 1.10 ± 1.52	0.19 ± 0.17 0.03 ± 0.03	[37]
MB layer	South Korea	5636	Gravimetric method and air sampling pump	TSP	N/A	4.42 2.25	[43]
MB 1 MB 2	Indiana, USA	200,000 180,000	Tapered Element Oscillating Microbalances (TEOM)	PM_{10}	N/A	0.42 ± 0.43 0.76 ± 0.66	[9]
Two HR.	Midwest, USA	250,000 per HR	TEOMs	Total	20.6 ± 22.5 *	N/A	[5]
HR layer	North Carolina, USA	103,000	TEOMs	$PM_{2.5}$ PM_{10} TSP	0.12 ± 0.26 6.03 ± 2.63 14.2 ± 5.23	N/A	[49]
HR 1 HR 2	Indiana, USA	200,000 180,000	Tapered Element Oscillating Microbalances (TEOM)	PM_{10}	N/A	0.54 ± 0.30 0.55 ± 0.34	[9]
HR layers	California, USA	32,500	Tapered element oscillating microbalance (TEOM)	$PM_{2.5}$ PM_{10} TSP	5.9 ± 12.6 33.4 ± 27.4 78.0 ± 42.7	N/A	[30]
HR layers	IOWA, USA	250,000	TEOMs	PM_{10} $PM_{2.5}$	8.16 ± 4.94 1.13 ± 1.16	0.39 ± 0.26 0.044 ± 0.04	[50]
Multilevel system	Sweden	13,500	Battery powered pump	TSP		1.8	[45]

AU = animal unit equivalent to 500 kg live mass, * $mgday^{-1}bird^{-1}$; N/A—Not available or not found; CC—Conventional cage; EC—Enriched Colony; CF—Cage-free; FR—Free range.

3.2. Effect of Bedding Materials on PM Levels

Cage-free housing commonly uses bedding materials on the floor for producing hens with litter floor to perform natural behaviors of dust bathing and foraging [51–58]. In Europe, litter floor distribution should include bedding material covering at least 33% (one-third) and 100% of total space in laying hens and broiler houses, respectively [51]. This litter floor is the main source of PM emissions in CF houses. Particulate matter production from bedding material can be influenced by the type of bedding materials, moisture content, depth of bedding material, replacing or cleaning frequency [52]. Bedding materials can be organic (wood shaving or chips, straw, paper, rice hulls, maize silage, plant husk, or grass) or inorganic (stone, sand, and clay) in origin and must be nontoxic, highly absorbent, and comfortable for animals [36,53]. The management of bedding materials has been studied to control PM concentrations or emissions in animal houses [54,55], as summarized in Table 3. Different types of bedding materials, including peat, clay pellets, chopped straw, wood shaving, chopped paper, or gravel, peat, and clay pellets, were compared. Peat and clay pellets have shown higher efficiencies in PM reduction ranging from 19 to 64% [56].

Table 3. Particulate matter emission due to different bedding materials used in the poultry housing system.

Bedding Material	Source	PM Sizes	PM Emission (mg/m^3)	References
Cornstalk chip	Broiler	TSP	6.5	[58]
Sugarcane top chips	Broiler	TSP	6.8	[58]
Wood shaving	Laying hens	TSP	2.3	[56]
Wood shaving	Broiler	$PM_{2.5}$ * PM_{10} *	1.05 20.3	[55]
Sawdust	Dairy farm	TSP	0.51	[59]
Wheat straw	Broiler	TSP	6.9	[58]
Rapeseed straw	Broiler	$PM_{2.5}$ * PM_{10} *	0.98 20.6	[55]
Rapeseed straw	Broiler	$PM_{2.5}$ * PM_{10} *	0.97 and 20.5	[55]
Clover straw	Broiler	TSP	6.7	[58]
Chopped straw	Laying hens	TSP	2.1	[56]
Straw	Dairy farm	TSP	0.53	[59]
Chopped palm spines	Broiler	TSP	6.5	[58]
Corn ear husks	Broiler	TSP	6.8	[58]
Silage maize	Broiler	$PM_{2.5}$ * PM_{10} *	0.85 21.0	[55]
Chopped paper	Laying hens	TSP	2.6	[56]
Peat	Laying hens	TSP	1.7	[56]
Compost	Dairy farm	TSP	1.38	[59]
Clay pellets	Laying hens	TSP	1.8	[56]
Gravel	Laying hens	TSP	4.7	[56]

* g $year^{-1} ap^{-1}$ (ap = animal place, inoccupation of 19%).

3.3. Effect of Lighting and Seasonal Variations on PM Levels

During the daytime, increased activities of birds lead to a higher PM concentration than the nighttime [60]. The concentration of $PM_{2.5}$, PM_{10}, and TSP were 151, 108, and 136% higher ($p < 0.05$) during the daytime (lights on) than at nighttime. During the daytime, birds were most active, ventilation rates were highest, and emissions rose. However, the ratio of $PM_{2.5}$ and PM_{10} decreases at night because of low bird activities and the settling down of PM_{10} concentration [37].

The emission of PM is seasonally dependent and varies over time (Table 4) [37,38]. PM concentration increases in the winter compared to fall, spring, and summer [4,37,38,50,61]. According to Li et al. (2011), the concentration of PM_{10} was found to be lower during summer relative to winter due to higher air temperature and ventilation rates [50]. In addition, hens tend to move less if there are under heat stress in summer because the higher indoor air temperature may cause stagger, stupor, and reduced activities, and thus result in lower dust generation from the litter, while the cold season increases layers' activities, thus generating higher PM from the poultry house litter floor [62]. Besides animal activities, house ventilation and litter moisture are critical for PM generations. Therefore, the total poultry house PM emissions could be higher in summer than in winter because of increased house ventilation and drier litter conditions [30].

Table 4. Particulate matter concentration (mg/m^3) as affected by seasons.

PM Size	Fall	Winter	Spring	Summer	References
PM_1	0.01	0.03	N/A	0.02	[63]
PM_1	75.6 ± 14.1	136.0 ± 12.8	53.5 ± 6.3	14.9 ± 1.2	[64]
PM_1	N/A	0.12 ± 0.00 *	0.09 ± 0.00 *	N/A	[65]
$PM_{2.5}$	81.6 ± 15.1	144.2 ± 14.5	58.1 ± 6.9	15.8 ± 1.1	[64]
$PM_{2.5}$	0.05	0.10	N/A	0.07	[63]
$PM_{2.5}$	0.09–0.11 ^{a}	0.09–0.20 ^{a}	0.07–0.12 ^{a}	0.06–0.10 ^{a}	[61]
$PM_{2.5}$	0.29 ± 0.22	0.43 ± 0.27	N/A	0.067 ± 0.055	[38]
$PM_{2.5}$	0.23 ± 0.15 #	0.30 ± 0.19 #	0.81 ± 0.87 #	2.46 ± 2.04 #	[37]
$PM_{2.5}$	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.03	0.08 ± 0.04	
$PM_{2.5}$	N/A	0.16 ± 0.006 *	0.10 ± 0.00 *	N/A	[65]
PM_4	0.32 ± 0.23	0.48 ± 0.31	N/A	0.074 ± 0.060	[38]
PM_{10}	0.10	0.24	N/A	0.15	[63]
PM_{10}	0.51–0.69 ^{a}	0.71–0.88 ^{a}	0.24–1.01 ^{a}	0.15–0.21 ^{a}	[61]
PM_{10}	94.8 ± 15.6	385.2 ± 16.6	183.0 ± 18.5	30.1 ± 1.9	[64]
PM_{10}	0.53 ± 0.35	0.69 ± 0.4	N/A	0.119 ± 0.011	[38]
PM_{10}	2.73 ± 1.91 #	2.82 ± 2.42 #	2.23 ± 2.08 #	2.51 ± 2.08 #	[37]
PM_{10}	0.50 ± 0.31	0.49 ± 0.43	0.16 ± 0.09	0.14 ± 0.08	
PM_{10}	N/A	0.49 ± 0.02 *	0.63 ± 0.02 *	0.56 ± 0.02 *	[65]
TSP	N/A	2.22–4.96 ^{a}	N/A	0.34–0.48 ^{a}	[61]
TSP	147.8 ± 18.3	983.2 ± 86.1	413.2 ± 39.8	49.6 ± 3.6	[64]
TSP	4.16 ± 2.19	4.98 ± 2.29	4.41 ± 2.14	4.00 ± 1.94	[43]
TSP	1.93 ± 0.82	3.29 ± 1.68	2.35 ± 1.15	1.76 ± 0.84	[43]

g day^{-1}AU^{-1}, * Kg$_{pm}$1000 bird^{-1}pc^{-1} (pc = production cycle), ^{a} µg/m^3, N/A—Not available or not found.

3.4. Effect of Ventilation System

PM emissions depend on the housing systems and ventilation types. Most of poultry housing systems are mechanically ventilation system that applies maximum ventilation in summer for removing extra heat and uses minimum ventilation in winter for moisture removing, which can improve air quality inside the house [66]. Poultry house ventilation rate affects the PM concentration [9]. Similarly, ventilation changes as affected by seasons that winter season has the highest concentration of PM among all four seasons [37]. Oppositely, increased ventilation during the summer dilutes the PM concentration [62]. Besides seasonal effect, housing style (e.g., natural ventilation vs. mechanical ventilation), ventilation types (e.g., negative vs. positive ventilation), and fan selection could also affect PM generations (Table 5). Measurements of PM in natural ventilation systems have higher variations as wind directions and speed are varying over time.

Table 5. Emission of PM due to various ventilation systems used in the housing system.

Location	Ventilation Type	Sensors	PM Size	PM Emission (mg d^{-1} bird^{-1})	PM Concentration (mg m^{-3})	References
China	TBM equipment with the main ventilation system	TSI 9306 dust sampler	TSP	N/A	18.65 (closed) 14.25 (open)	[39]
China	Double-tunnel ventilation with air inlet	Self-developed portable device	$PM_{2.5}$ PM_{10}	N/A	0.06 0.04	[67]

Table 5. *Cont.*

Location	Ventilation Type	Sensors	PM Size	PM Emission (mg d^{-1} $bird^{-1}$)	PM Concentration (mg m^{-3})	References
Mississippi, USA	Negative pressure ventilation	TSI DustTrak 8533	PM_1 $PM_{2.5}$ PM_4 PM_{10} TSP	N/A	0.148 0.149 0.151 0.160 0.169	[68]
North Carolina, USA	Tunnel-ventilation with 34 exhaust fans	Tapered element oscillating microbalance (TEOMs)	$PM_{2.5}$ PM_{10} TSP	0.37 ± 3.06 17.8 ± 14.9 43.1 ± 35.5	N/A	[49]
California, USA	Portable 122 cm exhaust fan	TEOMs	$PM_{2.5}$ PM_{10} TSP	0.006 ± 0.013 0.033 ± 0.027 0.078 ± 0.043	N/A	[30]
Saudi Arabia	Naturally	Particle counter device	$PM_{2.5}$ PM_{10} TSP	N/A	0.18 ± 0.06 4.81 ± 1.63 12.47 ± 5.2	[69]
	Mechanically	Particle counter device	$PM_{2.5}$ PM_{10} TSP	N/A	0.09 ± 0.05 2.26 ± 1.27 4.61 ± 3.1	

N/A—Not available or not found.

3.5. Effect of Indoor Temperature and Relative Humidity

Temperature and relative humidity (RH) are inversely proportional to each other. Increased temperature decreases RH and is directly influenced by ventilation rates within poultry houses [70]. Temperature and RH change seasonally and depend on weather conditions and experimental house design. During the winter, ventilation rates are decreased, and heaters are turned on to make a room warm, reducing RH. A decrease in RH increases PM concentration. However, ventilation rates are increased during the summer season to bring cold air or moisture from outside (cooling pad). The moisture from outside makes RH higher inside the house and decreases PM concentration by making heavy PM settle down. According to Lin et al. (2017), $PM_{2.5}$ and PM_{10} concentrations depend on RH due to ambient air [71]. Similarly, houses or rooms attached more to the outside environment possess higher RH due to individual room effects. Tang et al. (2020) tested the effect of different temperatures (21.1, 23.8, 26.4, and 29.2 °C) and RH (49.5, 74.7, 78.8, and 80.0%) on PM concentrations and found that PM_1, $PM_{2.5}$, PM_{10}, and TSP were significantly lower in higher RH and lower temperature treatments because RH could affect litter moisture [64]. In addition, several experiments used liquid spray (oil or water) to reduce PM concentration by increasing LMC and RH [24,72–76]. In addition, Yang et al. (2022) found that RH directly affects LMC and varies between rooms and within rooms [77]. Higher LMC within rooms results in lower PM levels [24,78]. That is why temperature and RH have a direct influence on PM levels.

3.6. Other Factors

3.6.1. Manure Cleaning Methods

Poultry manure management plays an important role in dust emissions because manure contributes about 50% of total dust emissions in most housing systems with a raised floor [18]. Several studies show that floor-raised houses (broilers or layers) where manure gets deposited on the floor over time possess potentially higher PM concentrations than other poultry housing [17,40]. Similarly, PM_{10} and $PM_{2.5}$ produced from deposited manure contribute up to 96% and 72% of total dust emissions, respectively, from poultry facilities [17]. In addition, poultry facilities having different kinds of manure removal or storage affects the PM concentration. For example, according to Chai et al. (2012), houses with MB usually have significantly higher dust concentrations than HR housing (manure deposited underneath the house) [9]. However, manures are removed continuously in

MB housing to decrease PM levels. Similarly, manure removal frequency also affects PM production. An increase in manure removal frequency has shown the highest PM reduction compared to less frequent or stored manure facilities [45]. For example, furnished cages with manure belts with a manure removal frequency of two times per week resulted in lower PM concentration and bacteria counts than floor-raised with manure storage.

3.6.2. Bird Age, Stocking Density, and Behaviors

The chickens' activity and dust emission depend on the birds' age in poultry housing [78]. Recent research on pullets found that an increase in pullets' age increases birds' activities and significantly affects or increases dust production ($p < 0.05$). Similarly, Vucemilo et al. (2007) also found that increasing broiler age affects PM levels significantly [79]. Chicken activities during feeding mainly increase PM_{10} and TSP in the chicken house [80]. However, the perching behaviors and dust bathing in open spaces showed high PM production compared to the feeding and drinking behaviors [78]. Moreover, PM emission is also affected by housing stocking density and bird weight [9]. PM levels are higher with the increase of birds' weight and stocking density.

4. Impacts of PM on the Health and Welfare of Chickens and Farm Workers

High levels of PM can negatively impact the health and welfare of animals and their caretakers. According to Zhao et al. (2016), PM acts as a major carrier for airborne bacteria and endotoxin, which, once inhaled, might cause harmful effects on the respiratory systems of animals and caretakers [81]. When toxins carried by PM_{10} (particle size less than 10 μm) reach the bloodstream after inhalation, they can harm the respiratory system, liver, kidneys, and nervous system [12,14,82]. On the other hand, PM is more harmful to humans and birds with pre-existing cardiac diseases like asthma, making breathing difficult [83]. A low level of ventilation rate within the animal house was linked to long-term lung function impairment in animals [20]. Higher PM_{10} levels can increase the risk of chronic bronchitis, cardiovascular illness, pneumonia lesions, asthma-like symptoms, and lung cancer in farmers and animals [21,22].

4.1. Impacts on Birds' Health, Behaviors, and Welfare

High PM concentrations have been linked to higher avian mortality rates [84]. Particulate matters contain various airborne bacteria and endotoxin, which negatively impact health and welfare issues of birds. When birds inhale dust particles with dust-borne pathogens (especially Mycoplasma species) damage occurs to mucosal surface cilia present in the trachea [85]. Particulate matter of size $PM_{2.5}$ was found to have lots of harmful microorganisms and endotoxins (Table 6) [86]. Long-term exposure to $PM_{2.5}$ has been linked to impaired lung function, and fraction size up to PM_{10} has increased mortality risk [83]. According to Roque et al. (2015), the endotoxin of dust helps decrease the percentage of cell-mediated immunity B cells ($CD3^{-}la^{+}$ B cells) in layers [87]. A decrease in cell-mediated immunity B cells causes birds to have difficulty fighting against poultry pathogens and several health issues. In addition, birds raised on litter floors evinced a higher incidence of lung damage due to higher PM emissions [88].

Table 6. Effects of various PM sizes or types on health, behavior, and welfare of birds.

PM Sizes/Types	Effects of PM on Health, Behavior, and Welfare	References
$PM_{2.5}$	Consists of a high level of microorganisms and endotoxin, which affects health	[86]
$PM_{2.5}$	Induces developmental cardiotoxicity in chicken embryos and hatchling chickens	[89]
$PM_{2.5}$	Impaired lung function	[83]
PM_{10}	Increased risk of mortality rates	

Table 6. *Cont.*

PM Sizes/Types	Effects of PM on Health, Behavior, and Welfare	References
PM_{10}	Increased risk of chronic bronchitis, cardiovascular illness, pneumonia lesions, asthma-like symptoms, and lung cancer	[21,22]
TSP	Decreased daily weight gain, increased lung inflammatory factors level, and may cause lung injury	[90]
Endotoxin+ dust	Decrease in cell-mediated immunity B-cell percentages	[87]

4.2. Human Health, Behaviors, and Welfare

Particulate matter in poultry houses can pollute the air and affect caretaker health. Poultry caretakers are at high risk due to occupational exposure to PM, leading to more respiratory hazards at work than in other work environments. Similarly, male poultry workers who smoke showed a substantially higher prevalence of chronic cough, chronic phlegm, and chronic bronchitis than nonsmokers [91]. The most common symptoms caused by PM in poultry workers are characterized by cough, phlegm, eye irritation, dyspnea, chest tightness, weariness, nasal congestion, wheezing, sneezing, nasal discharge, headache, throat irritation, and fever [12,19–22,83].

Inhaled PM can penetrate deeper into the respiratory airways, impairing human respiratory health and leading to a rise in chronic bronchitis, allergic responses, chronic cough, phlegm, and asthma-like symptoms amongst caretakers [12,13,19,20]. It is found that long-term exposure to PM increases obstructive pulmonary disorder rates [23]. Moreover, high asthmatic (42.5%) and nasal (51.1%) symptoms are observed in poultry workers. In farmers, higher PM_{10} concentrations can cause chronic bronchitis, asthma-like symptoms, cardiovascular disease, pneumonia lesions, chronic obstructive pulmonary disease (COPD), and lung cancer [21–23]. The relationship between PM levels and COPD cases or human mortality has been investigated. A 10 g m^{-3} rise in $PM_{2.5}$ was shown to be associated with a 24% increase in cardiovascular events and a 76% increase in mortality [92], while residents living near a high-volume highway would experience a 33% increase in COPD incidence for every 7 g m^{-3} increase in PM_{10} [93]. PM exposure affects children's lung development and long-term lung function [94]. In addition, PM of different sizes is dangerous to humans with pre-existing cardiovascular diseases, such as asthma [12,83].

Among the different types of PM, $PM_{2.5}$ and PM_{10} have adverse effects on human health (Table 7). The mass concentrations of PM_{10} and $PM_{2.5}$ have commonly been used as an indicator for defining PM that significantly affects health [94]. Inhalable particles that are tiny enough to enter the thoracic area of the respiratory system are included in PM_{10} and $PM_{2.5}$. In most places in Europe, $PM_{2.5}$ accounts for 50–70% of PM_{10}. Short-term and long-term exposure to PM_{10} negatively impacts the respiratory system and increases mortality rates, respectively, while long-term exposure to $PM_{2.5}$ increases the risk of cardiopulmonary mortality. According to Dai et al. (2017), the distribution of $PM_{2.5}$ in high-rise and manure-belt houses was found to damage human alveolar epithelial cells (A549 cell) [95]. $PM_{2.5}$ collected reduced the viability of A549 cells in a time- and dose-dependent manner and produced an inflammatory response. Despite evidence confirming the adverse effects of poultry house exposures on employees' respiratory health, the industry has mainly ignored the health of exposed workers [35]. The World Health Organization has stated the need to monitor PM_{10} and $PM_{2.5}$ levels in many countries and to estimate population exposure, which will aid local authorities in developing strategies to improve air quality [94].

Table 7. Effects of different PM sizes on health, behavior, and welfare of caretakers.

PM Sizes/Types	Effects of PM on Health, Behavior, and Welfare	References
$PM_{2.5}$	Greater risk to human health	[12,14]
$PM_{2.5}$	Damage human alveolar epithelial cells (A549 cells) and cause an inflammatory response	[95]
$PM_{2.5}$ (long-term exposure)	Increases the risk of cardiopulmonary mortality	[11,94]
$PM_{2.5}$ (10,000 mg/m^3)	24% increase in cardiovascular events and a 76% increase in mortality	[92]
PM_{10}	Premature death in humans with heart or lung disease Nonfatal heart attacks, irregular heartbeats, aggravated asthma, decreased lung function, irritation of the airways, coughing or difficulty breathing	[12,13]
PM_{10} (With endotoxin)	Affects the respiratory system, liver, kidneys, and nervous system, and may even enter the bloodstream	[12,14,82]
PM_{10}	Respiratory problems Increased mortality and morbidity rates	[11,94]
PM_{10} (High concentration)	Chronic bronchitis, asthma-like symptoms, cardiovascular disease, lung cancer, COPD, and pneumonia lesions.	[21–23]
PM_{10} (every increase in 7000 mg/m^3)	33% increase in COPD incidence	[93]
TSP	Higher asthmatic (42.5%) and nasal (51.1%) symptoms	[23]
TSP	Over-shift increase in respiratory symptoms and a decrease in pulmonary function tests were found. Causes harmful effects on the bronchi	[96]
PM > 0.1 mg/m^3	Coughing, chronic phlegm, and bronchitis	[97]
Organic dust	Acute inflammation and chronic bronchitis	[98]

4.3. Poultry Production

Air quality is essential to increase production and plays an important role at an early stage of development. According to Willis et al. (1987), birds grow faster in a less dusty indoor environment than in a higher dust environment [99]. Birds' body weight was recorded as 45 g and 165 g heavier at four and seven WOA in the less dusty environment than in the dusty environment. A dusty environment with high PM concentration can affect BW gain, reduce production performance, and cause specific humoral immune responsiveness in broilers [23,34,95]. According to Lai et al. (2009), a high level of dust-containing pathogens can cause a decrease in body weight gain, alter heart morphology, and increase immune reactivity [100]. Similarly, increased inhalation of PM causes lesions in the respiratory tract, which provides space to cause pathogenic effects of microorganisms [84,101]. With increased pathogenic effects of microorganisms, birds' growth rate decreased and even increased the chances of mortality. Thus, poor air quality directly harms production and increases economic loss.

5. Mitigation Strategies Suppressing PM Levels in Poultry Houses

The high level of PM in poultry facilities is a major concern for the health and welfare of animals and their caretakers [102–107]. Among different PM sizes, PM_{10} and $PM_{2.5}$ levels are considered measurement factors for most organizations and countries because of their harmful effects on the health and welfare of caretakers (Table 8). The World Health Organization (WHO) recently amended the ambient air quality standards in 2021 and proposed the maximum of PM_{10} to be 15 μg/m^3 for the annual average and 45 μg/m^3 for the 24-h mean, while for $PM_{2.5}$ to be 5 μg/m^3 for the annual average and 15 μg/m^3 for the 24-h mean [11,106]. According to the EPA (2022), the National Ambient Air Quality Standard (NAAQS) has set an exposure limit of $PM_{2.5}$ and PM_{10} as 35 μg/m^3 and 150 μg/m^3, respectively, for 24 h (98th percentile, averaged over 3 years) [103]. Therefore, everyone must follow OEL guidelines to improve the caretaker's health.

Table 8. Recommended guidelines for PM on occupational exposure limit of various countries or organizations.

Country/Organization	Occupational Exposure Limit	References
World Health Organization	$PM_{2.5}$: 5 μg/m^3 annual mean & 15 μg/m^3 24-h mean (2011 standard)	[11]
	$PM_{2.5}$: 10 μg/m^3 annual mean & 25 μg/m^3 24-h mean (2005 standard)	[106]
	PM_{10}: 15 μg/m^3 annual mean & 45 μg/m^3 24-h mean (2011 standard)	[11]
	PM_{10}: 20 μg/m^3 annual mean & 50 μg/m^3 24-h mean (2005 standard)	[106]
USA (EPA)	$PM_{2.5}$: 35 μg/m^3 24-h mean	[13]
	PM_{10}: 150 μg/m^3 24-h mean	[13]
	$PM_{2.5}$: 12 μg/m^3 annual mean (primary standard *)	[103]
	$PM_{2.5}$: 15 μg/m^3 annual mean (secondary standard *)	[103]
USA (Occupational Safety and Health Administration)	Total dust 10 mg/m^3 and respirable friction dust 5 mg/m^3 (regulator limit of 8-h time-weighted average)	[105]
Australia	$PM_{2.5}$: 50 μg/m^3 (1 h average) & 25 μg/m^3 (24-h average)	[104]
UK	Total and respirable dust limits are 10 and 5 mg/m^3, respectively	[107]

* Primary as sensitive health populations like asthmatic, elderly, and children. Secondary as welfare protection against damage and visibility.

6. Particulate Matter Emission Mitigating Strategies

The PM concentration in poultry housing is primarily affected by housing and feeding, animal species, stocking density, lighting duration, environment conditions (season), and existing mitigation practices [22,24,72,108]. It is important to possess a deep knowledge of PM morphology to evaluate their effects and propose the best mitigating technologies in animal housing. Particulate matter mitigating strategies can be classified into three different groups: dilution and effective room air distribution, source-control techniques to reduce PM from the source, and PM removal or cleaning techniques by using acid scrubbers, electrostatic precipitators, or ionizers [109]. Other techniques for improving air quality are oil spraying, manure handling, and electrolyzed water spray [24]. Controlling the living space environment, including temperature, humidity, air quality, and litter quality, is critical for poultry well-being [110]. Variations in indoor air quality have been linked to various factors, including barn architecture, manure management, animal densities, feed regimens, building ventilation, and farm management practices. Therefore, various biochemical, chemical, managerial, physical, and physiological practices must be implemented to decrease PM significantly lower than recommended guidelines (Figure 3).

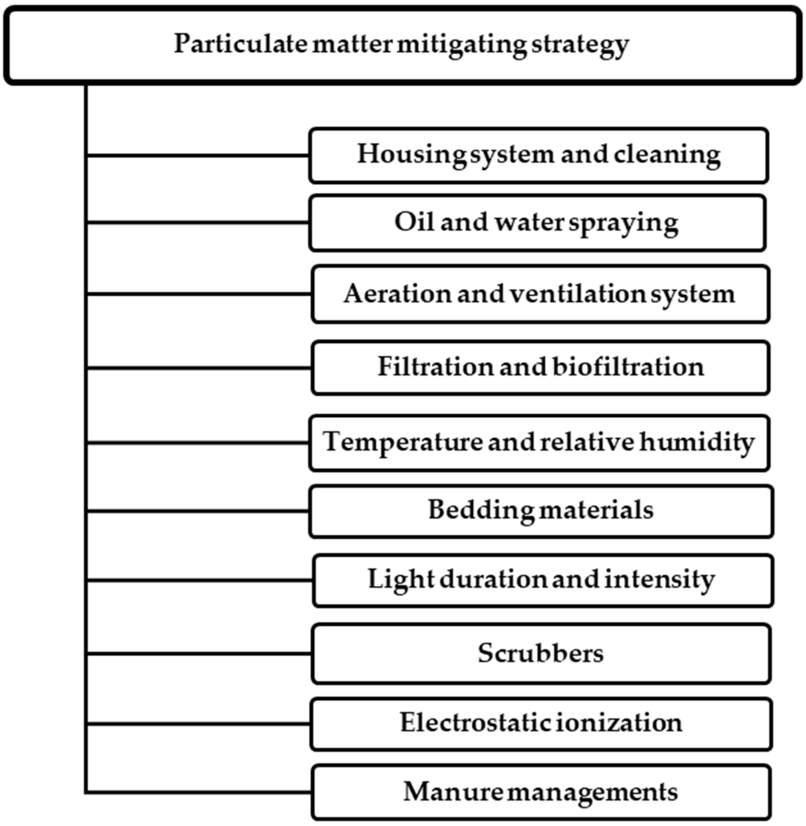

Figure 3. Overview of the PM emission mitigating strategy used in poultry housing.

6.1. Housing Systems and Cleaning

Particulate matter emission differs according to housing types. Dust concentrations in caged buildings are influenced by cage design and rearing practices, but dust levels in floor housing are determined by litter management, hen age, temperature, and humidity control [41,78]. The air quality in CF houses is generally worse than in caged houses. Usually, PM concentration is higher in CF houses than in other housing types because of litter accumulation and hen activities on the floor [24,40]. In the floor housing system, an average concentration of respirable ambient dust of 0.37 mg/m^3 was detected, which was more significant than average values in the caged system (0.13 mg/m^3). Similarly, Le Bouquin et al. (2013) also found the highest concentration of dust (1.19 mg/m^3) in AV housing [41]. The researchers evaluated PM levels in three-layer houses (AV, CC, and EC) and discovered that the daily mean PM_{10} level in AV was about six to nine times higher compared to CC and EC [40]. The emission rates for PM_{10} and $PM_{2.5}$ were highest because of increased activities on the littered floor [40]. However, in CC and EC, PM emissions were similar, accounting for 16% of AV PM_{10} ER and 10–20% of AV $PM_{2.5}$ ER, respectively. Thus, caged hen housing shows the lowest dust concentration, almost four to five times lower than floor-raised AV housing systems [111]. As a result, the type of housing and the amount of litter significantly impacted air quality. According to Guarino et al. (1999), PM concentration inside the farm were significantly higher during scraper cleaning and feed distribution [84]. As a result, reducing PM generation and emissions is critical for maintaining the health and well-being of laying hens and caregivers while also increasing the environmental stewardship production operation. Thus, housing types and cleaning procedures are vital in controlling PM emissions.

6.2. Oil and Water Spraying

Oil and water spraying in poultry housing helps to control indoor PM concentration. Spraying liquid agents, such as tap water, acidic water, electrolyzed water, or a combination of water and soybean or canola oil, over poultry buildings has been studied to lower PM levels and disinfect the houses [24,72–76]. According to Ogink et al. (2012), Spraying water on top of litter at an application rate of 150 to 600 mL m^{-2} reduced PM_{10} and $PM_{2.5}$ emissions by 18 to 64% in an aviary hen house but increased NH_3 emissions by 21 to 65% [76]. High liquid spray dosages decrease PM significantly while increasing NH_3 levels due to the accumulation of litter moisture [112]. A spray dose of pH3 and 25-mL kg^{-1} dry litter d^{-1} showed a good combination for controlling PM levels in littered CF hen houses without creating unwanted increases in NH_3 emissions [24]. Spraying a liquid agent like electrolyzed water over the litter of CF hen houses has been demonstrated to decrease PM successfully. Cautions should be paid as spraying water may lead to corrosion of metal equipment in poultry facilities [24].

Research on oil and water spraying shows significant PM and airborne bacteria reductions (Table 9). Total dust, airborne bacteria, and fungi were significantly reduced by soybean oil for 24 h after spraying [113]. Particulate matter removal efficiency of oil and water spray ranges from 18 to 89%. Increased spraying frequency can help reduce PM emissions even further, but it can also make surfaces oily and slippery, posing a safety risk to workers and animals [114].

Table 9. Particulate matter reduction with liquid spray.

Spray System	Working Principle	Oil or Water Type	Application Rate (mL $m^{-2}d^{-1}$)	PM Size	PM Reduction (%)	References
Electrospray	Engineered water nanostructures	Water	$1 \times 10^{5\,\#}$	PM_{15}	83	[115]
BETE fog spray nozzle	Droplet confine particles in a litter	Acidic electrolyzed water (0.1% NaCl solution and addition of 85% phosphoric acid)	125 250 375	Total PM	71 ± 3 81 ± 1 89 ± 1	[24]
Fixed oil spraying system + Driving oil spraying vehicle	A fog of oil droplets + A spray of fine droplets	Rapeseed oil	12 15 30	PM_{10} and $PM_{2.5}$	60 and 53 21 and31 32 and 38	[73]
Hand-held spraying lance	A spray of fine droplets	Rapeseed oil	15 30 45	PM_{10} $PM_{2.5}$	27, 62, 82 71, 83, 94	[73]
Full cone nozzles	Spraying	Rapeseed oil with water	10%	Total dust	30–50	[54]
Sprayers with electrolytic cell generator	Droplet confine particles in a litter	Neutral electrolyzed water (pH 8.2)	216 *	Airborne dust	34	[116]
Battery backpack sprayer	Water fogged	Water	150 * 300 * 600 *	PM_{10} $PM_{2.5}$	18 and 44 48 and 59 64 and 64	[76]
Fixed oil spraying system	A spray of fine droplets	Rapeseed oil	6 24	$PM_{2.5}$ PM_{10}	84 and 48 80 and 87	[75]
Spray nozzle	Droplets confine particles in a litter	Rapeseed oil + Water	5 [a]	Airborne dust	80–85	[117]
Full cone nozzles	Droplet confine particles in a litter	Rapeseed oil	8 16	PM_{10} $PM_{2.5}$	59 and 64 81 and 74	[74]
Backpack sprayer	Sprinkling	Canola oil	10–30 *	Total	37–89	[114]
Backpack sprayer	Sprinkled	Canola oil	Six application rates	Respirable Inhalable	71 76	[114]

* ml m^{-2}; # mm^3 min^{-1} for data log interval of 1 s; [a] g oil $day^{-1}pig^{-1}$.

6.3. Filtration and Biofiltration

Filtration is one of the most well-known and extensively applied methods for removing particles from an air stream (Table 10). Filtration typically occurs through dry methods (without adding water), including impaction, interception, diffusion, and electrostatic and gravitational deposition [118]. Interception and impaction are major processes for larger particles, but diffusion is the primary mechanism for particles less than 0.5 μ [108]. Filters are usually used to remove dust particles from AFOs, while filters that utilize water as a scrubber media may catch NH_3 gas from the air in poultry houses and clean it.

For many years, water filters, also known as trickling filters, have eliminated PM, NH_3, sulfur compounds, and nitrous oxides in commercial operations [119]. Biofilters are generally designed to control NH_3, with PM as a secondary concern [120], and help to biologically transform pollutants, such as NH_3 gas, into inert forms [121,122]. Similarly, biofilters commonly use soil, compost, peat, activated carbon, municipal trash, bark, trimmings, and leaves as organic filter media [123].

Table 10. Air filtration systems used to mitigate PM emissions.

Filter/Biofilter	PM Size	PM Reduction (%)	References
Wood-chip Bio-filter 127 mm 254 mm	PM_{10} TSP	62 and 89.7 62.9 and 96.3	[9]
Stuffnix dry filter U-bend baffle filter	$PM_{2.5}$ and PM_{10}	41 and 64 19 and 22	[44]
Dry filter	PM concentrations PM emissions	55 72	[62]
Dry filter	$PM_{2.5}$ PM_{10}	7.1 40.7	[66]
Biotrickling filter and denitrification EBRT * = 3 s EBRT = 0.71 s EBRT = 3.6 s	PM_{10}	38 60 69	[124]
Stuffnix dry filter	Fine dust	20–60	[125]
Trickling biofilter using acidified water	PM_{10}	>80	[126]
Bio-filter	TSP	79–96	[127]

* EBRT = Empty bed air residence time.

6.4. Bedding Materials

Poultry litter/bedding material is well-known as the mixture of initial bedding material and the manure deposited by the birds on the floor [55]. Bedding material is the main contributor to PM emission from CF poultry facilities than caged. According to Van Harn et al. (2012), using different kinds of bedding material significantly reduces PM emissions; maize silage has shown a 19% $PM_{2.5}$ reduction compared to wood shaving [55]. However, it does not show any significant differences in PM_{10} reduction. Similarly, when different kinds of bedding materials (chopped straw, gravel, peat, wood shaving, chopped paper, or clay pellets) were used in layer housing, peat or clay pellets resulted in lower PM production [54].

Several studies have shown that bedding increases dust concentrations, so changing bedding materials might be an alternative to reduce PM emissions [54,55] (Table 11). However, changing bedding materials in every flock (broilers) is impossible from an economic point of view, so there is a general trend in the US of reusing litter for several flocks [128]. Reusing bedding material might be a good idea to increase profitability, but it also inherits the challenges of higher PM emissions, so deep littering or topping of bedding materials can be an alternate way to reduce PM emissions from the farm. According to Bist et al. (unpublished), top application of different bedding materials (fine wood shaving, large wood shaving, and aspen wood chips) over reused litter significantly reduced PM concentration by up to 40%. Moreover, using deep bedding material has reported many beneficial aspects like increased growth rate, weight gain, and feed conversion ratio in poultry [129,130].

Table 11. Particulate matter reduction by using different kinds of bedding materials.

Bedding Material	PM Sizes	PM Reduction (%)	References
Silage maize Wood shaving Wheat straw Rapeseed straw	$PM_{2.5}$ *	19%, but No significant difference between wood shaving, wheat straw, and rapeseed straw	[55]
chopped straw gravel peat wood shaving chopped paper clay pellets	Total dust	19–64% reduction by clay pellets and peat compared to other	[56]
Wheat straw Clover straw Cornstalk chip Sugarcane top chips Chopped palm spines Corn ear husks	Airborne dust	No significant difference between materials	[58]
Compost Straw Sawdust	Total dust	61% (straw) and 63% (sawdust) than compost	[59]
Chopped hay Chopped straw	Total dust	Significant effects	[131]

* in comparison to Silage maize.

6.5. Scrubbers

Scrubbers effectively remove air pollutants from poultry housing (Table 12). Scrubbers help remove airborne dust, bacteria, NH_3, and even CO_2 with the help of a multi-stage air scrubber design [132,133]. According to Zhao et al. (2011), three acid scrubbers (double-stage scrubber with filter, double-stage scrubber with a biofilter, and triple-stage scrubber) used in the experiment reduced PM_{10} by 61–93% and $PM_{2.5}$ by 47–90% [133]. The double-stage acid scrubber reduced dust levels significantly higher than the triple-stage acid scrubber. Along with PM reduction, this multi-stage acid scrubber significantly reduced airborne total bacteria concentration from 46% to 85%. A scrubber can decrease the total dust emissions and airborne bacteria concentration by up to 88% and 85%, respectively.

Table 12. Particulate matter and airborne bacteria reduction using scrubbers.

Scrubbers	$PM_{2.5}$ (%)	PM_{10} (%)	TSP (%)	Airborne Total Bacteria (%)	References
Electrostatic spray wet scrubber	85–88	85–94	N/A	N/A	[134]
Chemical (90% NH_3 reduction) Air Scrubber	28	33	N/A	N/A	[135]
Chemical (70% NH_3 reduction) Air Scrubber	33	41	N/A	N/A	[135]
Multiple pollutants scrubber	42	43	N/A	N/A	[132]

Table 12. *Cont.*

Scrubbers	$PM_{2.5}$ (%)	PM_{10} (%)	TSP (%)	Airborne Total Bacteria (%)	References
Disinfectant Scrubber media: water Peracetic acid Ozone	N/A	N/A	88 78 48	70	[136]
Multi-stage scrubber	47–90	61–93	N/A	46–85	[133]
Bio-scrubber	N/A	N/A	22	N/A	[127]

N/A = not available or not found.

6.6. Electrostatic Ionization

For many years, the electrostatic ionization technique has been used to lower PM levels in AFOs. Recently, attempts have been made to employ the technology in animal housing conditions, and several studies have demonstrated the efficiency of this control technique in lowering airborne PM and bacteria [8,137–142]. For example, Mitchell and Waltman (2003) tested an electrostatic charging system (ESCS; −30 K Vdc and 0.2 mA) in the hatching cabinet and reduced dust from 77–79% [138]. Similarly, ESCS decreased Enterobacteriaceae and salmonella bacteria in the air from 93 to 96% and 33 to 83%, respectively. Furthermore, recent research used the prototype electrostatic precipitator (ESP) technique in different ventilation or weather condition (hot, warm, and cold weather) and found $PM_{2.5}$ and PM_{10} reductions up to 97.8% and 99.0%, respectively [143]. Therefore, various research on electrostatic ionization has shown PM and airborne bacteria reduction up to 94 and 96%, respectively (Table 13).

Table 13. Particulate matter and airborne bacteria reduction with electrostatic charging.

Control Technology	Charging Units	Source	$PM_{2.5}$ (%)	PM_{10} (%)	Total Dust (%)	Airborne Bacteria (%)	References
Prototype ESP under hot, warm and cold weather	0.545 kV mm^{-1}	Poultry	86.9 94.4 97.8	90.8 97.1 99.0	N/A	N/A	[143]
Electrostatic particle ionization	Electrode −30 kV with 2 mA current	HR hen house	66 * 30 #	68 * 36 #	68 * 45 #	N/A	[68]
Negative ionization system Positive ionization system	Electrode −30 kV with 2 mA current Electrode +30 kV with 2 mA current	Broiler	49 6	68 0	N/A	N/A	[73]
ESP	Electrode +30 kV with 0.2–1.0 mA current	CF hen	45.3	57.0	N/A	N/A	[66]
Optimized ESP	9.6 to 13.6 KV with air velocity 0.8 to 2.2 m/s	Laying hen	86	84	82	N/A	[142]
Prototype ESP	+30 kVdc and <1 mA	Laying hen	45	57	N/A	N/A	[140]
Air Ionization	−30 kVdc and 0.9 mA	Broiler	10	36	N/A	N/A	[139]
ESCS	25K–30K Vdc and 2 mA	HR layer house	N/A	36	48	N/A	[144]
ESCS	−30 kVdc and 2 mA	Broiler	N/A	N/A	43	N/A	[8]
ESCS	−30 kVdc and <0.5 mA	Broiler breeder	N/A	N/A	61	67	[145]
ESCS	−30 kVdc and 0.2 mA	Hatching cabinets	N/A	N/A	77–79	93–96% Enterobacteriaceae 33–83% Salmonella	[138]
ESCS	−20 kVdc and 0.5 mA	Hatching cabinets	N/A	N/A	94	93% Enterobacteriaceae	[137]
ESCS	N/A	Swine	N/A	N/A	57–66	N/A	[146]

* Spring to summer, # Late fall to spring, N/A = not available or not found; ESP—electrostatic precipitator; ESCS—electrostatic charging system.

6.7. Other Management Practices

6.7.1. Aeration and Ventilation System

Aeration (Airflow speed) exhibited a significant and inverse relationship with PM and NH_3 concentrations but a significant and direct relationship with temperature [80]. The contradiction between maintaining temperature and increased ventilation must be implemented to improve the air quality in the layer house. When there is insufficient ventilation, the concentration of air pollutants can build up to dangerous levels [147]. During the colder seasons, ventilation is used to remove moisture and manage humidity levels, whereas during the warmer seasons, ventilation is used to keep interior temperatures within the poultry barn's thermal neutral zone. Furthermore, mechanical and natural ventilation systems help to dilute NH_3 and PM concentrations by delivering fresh air into the indoor environment [148]. The mixing of air induced by the air inlets and exhaust fans might impact PM levels within the barn when mechanical ventilation is used. Decreased ventilation can cause dust concentrations to drop because of increased moisture content in air and litter compared to high ventilation [70]. However, houses with extremely high ventilation rates or natural ventilation resulted in decreased dust levels.

6.7.2. Lighting Management

Lighting programs are very important for causing variation in PM concentration [111] and strongly affect birds' activities by changing circadian rhythms [149]. For example, particle formation rates in a layer house were significantly higher during light periods than during dark [25]. Similarly, the photoperiod duration shows increased dust emission from poultry housing as the light period increases birds' activities. The mean respirable PM level is higher in light periods than in dark periods in broiler housing [150]. According to Calvet et al. (2009), average dust concentrations during the daytime are four times higher than during dark periods [149]. Therefore, adjusting light duration and intensity can help to reduce PM emissions from the farm.

6.7.3. Precision Control of Indoor Temperature and Relative Humidity

Temperature and RH are highly influenced by ventilation rates within poultry houses [70]. Particulate matter emissions depend on indoor RH and temperature. High RH and low temperature within the housing capture dust particles due to increased air moisture content. Similarly, higher RH due to low ventilation makes dust heavy and settle down, thus helping to lower PM emissions [70]. However, housing's extremely high ventilation and natural ventilation rates can decrease PM emissions by pulling out PM from farms. Similarly, Tang et al. (2020) found that low temperature and high RH reduce PM emissions at higher levels, so controlling temperature and RH inside the house can help to decrease PM emissions from poultry houses [64].

7. Summary

Particulate matters (PM) found in poultry houses are biological, organic, and inorganic in composition, which originated from bedding materials, feathers, feeds, skin, excreta, bacteria, and feathers. Fine PM such as $PM_{2.5}$ is crucial in affecting the health and well-being of birds and caretakers as that can enter animals' respiratory system easier. According to the WHO, the occupational exposure limits of $PM_{2.5}$ annual mean and 24-h mean should not exceed 5 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively. The levels of PM in poultry houses could be 100 times of WHO limit or higher (e.g., $PM_{2.5}$ levels in cage-free henhouse are higher than 1500 $\mu g/m^3$ in most time of the year), and thus affect animals' health and welfare, including eye irritation, throat irritation, cough, phlegm, chest tightness, sneezing, headache, fever, nasal congestion, and wheezing, especially in cold periods when the house will have limited ventilation. Furthermore, long-term exposure to PM increases obstructive pulmonary disorder, chronic bronchitis, chronic obstructive pulmonary disease, pneumonia lesions, cardiovascular disease, asthma-like symptoms, lung cancer, or even mortality in humans. Similarly, a higher level of PM with endotoxin in birds causes impaired lung function, chronic bronchitis, pneumonia lesions, cardiovascular illness, and cardiotoxicity in chicken embryos and hatchling chickens and might increase the risk of mortality rates. That is why it is very important to identify primary emissions factors and investigate PM mitigating strategies.

PM emissions depend on various factors and changes according to climatic conditions, housing type, applied manure management strategies, ventilation system, temperature and relative humidity, bird numbers, and bedding materials used. The factors that release significantly high PM levels must be managed and decreased to preserve and improve the environment, and human and animal health and welfare. Several studies have shown significant PM reduction by applying biochemical, chemical, managerial, physical, and physiological practices, which can be managing housing system and cleaning, light intensity, oil and water spraying, filtration and biofiltration, acid scrubber, bedding materials, and electrostatic ionization. Single or integrated mitigation has shown significant PM reduction in the past. Future research must be implemented by including integrated mitigating strategies to obtain much better results to improve air quality in poultry houses and enhance the health of both caretakers and birds. In addition, mitigation strategies could be cost prohibitive and have side effects. For instance, an acid scrubber has up to 95% efficiency in mitigating both dust and NH_3, but the cost for installing the system is a primary barrier; the water spray has a lower cost in controlling PM generations in poultry houses, but the increased NH_3 should be considered in quantifying the mitigation efficiency and costs. Additional strategies such as litter additives and new bedding will be needed for NH_3 control if water spray results in higher NH_3 generations. Therefore, poultry farms should select mitigation strategies based on a number of considerations, such as farm location, climate conditions, environmental policies, and available resources (assistance programs).

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