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Effectiveness and Concentration Distribution of Negative Air Ions on Human Health in Indoor Environment

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Abstract: Negative air ions (NAIs) in indoor environments have been suggested to positively impact human health by effectively reducing particulate contamination and gaseous pollutants, as well as inhibiting the growth of microorganisms, bacteria and viruses. This study investigates the common ionizers with different module types, and the mechanism of NAIs for enhancing indoor air quality, as well as the positive and negative impacts on human health. The association between NAI concentrations and human health outcomes is examined, and alternative measures to balance beneficial and unavailing effects are investigated. While NAIs demonstrate efficacy in removing particulate pollutants, alleviating depression, enhancing cognitive function and even stimulating sympathetic activity, it is pertinent to acknowledge the presence of contradictory findings concerning their effects on cardiac autonomic function and respiratory physiology. To address this complexity, it is imperative to consider alternative measures that strike a balance between the beneficial and unavailing effects of NAIs. These measures can encompass a general assessment of the characteristics of particulate pollutants, a strategic selection of ionizer technologies, and adherence to the recommended optimal concentration thresholds of NAIs.

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0 Introduction

Negative air ions (NAIs), often referred to as "air vitamins", are significant factors in assessing air quality. In natural environments such as forests, waterfalls and torrential rains, NAIs are abundant. NAIs are typically found in molecular clusters, with concentrations ranging from approximately 5.0×10^3 to 1.0×10^5 ion/cm^3[1]. High NAI concentrations can be found as high as 0.5×10^5 ion/cm^3 near waterfalls, while in urban areas and indoor environments, it drops to several hundreds or lower[2]. Artificial methods can produce higher concentrations of NAIs[3], thus providing substantially higher energy compared to naturally generated NAIs. This is achieved by using ionizing radiation or high-voltage potentials, which supply sufficient energy to either remove electrons from neutral air molecules or allow these molecules to gain electrons, leading to the formation of ions[4-5].

NAIs have been widely applied in air purification to remove particulate pollutants in indoor environments[6-7], to induce the decomposition of indoor organic pollutants[8], and to enable effective disinfection of aerosolized *Escherichia coli*, *Salmonella typhimurium* and *Staphylococcus epidermidis* air microorganisms[9-11]. An environment favorable for human living should correspond to the following requirements[12]: air ion concentration within $4.0\times10^2-5.0\times10^4$ ion/cm^3, and unipolarity coefficient K within $0.4-1.0$. That is to say, the concentration of NAIs should be at least equal to or greater than the concentration of the positive air ions (PAIs).

In aerosol airborne, NAIs and PAIs inevitably coexist with particulate contamination, gaseous pollutants, microorganisms, bacteria and viruses, etc. Some of them are directly or indirectly harmful to human health. For example, each 10.0 μg/m^3 increase in chronic exposure to fine particulate matter 2.5 ($PM_{2.5}$) is associated with a significant rise in the risks of major cardiovascular and pulmonary events, ranging from 8% to over 20%[13]. Exposure to $PM_{2.5}$ can induce an increase in lipid peroxidation, vascular inflammation, endothelial cell injury initiation, respiratory diseases, and coronary and carotid atherosclerosis. $PM_{2.5}$ can also cause atherosclerotic vascular plaque rupture myocardial infarction, and stroke by activating metalloproteinase.

The most significant contribution of this study is to summarize the effectiveness and concentration level of NAIs on human health, especially in enclosed environments. Section 1 introduces the common ionizers with different module types. Section 2 presents the

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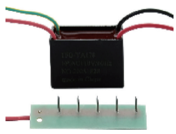
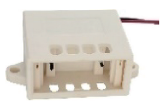
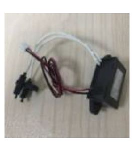
mechanism of NAIs for improving indoor air environments. Section 3 collects the direct and indirect effects of NAIs on human health. Section 4 discusses the NAI concentration distribution, and provides the alternative measures to balance the beneficial and unavailing effects of NAIs.

1 Common Ionizers with Different Module Types

To improve air quality and to enhance a healthy environment, ionizers are frequently utilized in residences, workplaces, medical institutions and public areas. Currently, there is a vast array of ionizers available on the market, each with unique design, performance and efficiency features. This variety stems from changes in consumer demands and technological advancements. The ionizer information about various module types and ion generation rates has been gathered from Amazon. com to thoroughly grasp the functionality and variety of uses of ionizers.

Table 1 presents the variable density of common ionizers with different module types. Their ion outputs are in the range of 2.0×10^{9} ion/s to 1.2×10^{13} ion/s. The ion concentration is different at varying distances from emitting electrodes. The ion concentration gradually decays with the increasing distance. Taking the ion output with 1.0×10^{13} ion/s as an example, there is an attenuation of the order of approximately one-tenth that occurs at a distance of 3.0 cm. The rated voltages of the tabulated ionizers are in the kilovolt level, and the rated powers are less than 1.0 W.

Table 1 Variable density of common ionizers with different module types

Module type	Ion type	Image	Ion output/(ion/s)	Ion concentration/(ion/cm^3)	Voltage/kV
TFB-YA178	NAI		1.0×10^{13}	$C_{NAI} > 1.1 \times 10^{12}$ (2.9 cm from emitter)	NV: −7.5
TFB-YA1102	BAI		—	$C_{PAI} > 1.5 \times 10^{8}$; $C_{NAI} > 2.0 \times 10^{8}$ (15.0 cm from emitter)	PV: 2.0±0.5; NV: −2.5±0.5
TFB-YD1278	BAI		—	$C_{PAI} > 4.0 \times 10^{10}$; $C_{NAI} > 8.0 \times 10^{10}$ (15.0 cm from emitter)	PV: 3.0±0.5 NV: −3.0±0.5
XHJ-D12F	NAI		—	$C_{NAI} > 1.9 \times 10^{12}$ (2.9 cm from emitter)	NV: −9.5
TFB-YD12102DJ1	NAI		—	$C_{NAI} > 1.0 \times 10^{6}$ (15.0 cm from emitter)	NV: −7.5±0.5
MIG-ION-12V-NP	NAI		1.2×10^{13}	$C_{NAI} > 1.9 \times 10^{12}$ (2.9 cm from emitter)	NV: −9.5
1XDC	NAI		—	$C_{NAI} > 7.0 \times 10^{6}$ (10.0 cm from emitter)	NV: −3.8±0.5

Notes: BAI—bipolar air ion; C_{NAI}—concentration of NAIs; C_{PAI}—concentration of PAIs; PV—positive voltage; NV—negative voltage.

2 Mechanisms of Improving Indoor Air Environments

Under NAIs in an indoor environment, there are different mechanisms involved in the removal of aerosol particles and the decomposition of organic pollutants.

2.1 Removal mechanism of aerosol particles

If the oppositely charged particles are present in an enclosed space aerosol, the electrostatic forces cause the particles to attract each other. This process coagulates ultrafine and fine particles into large particles. The common filters are generally less efficient at removing ultrafine and fine particles. Fortunately, the coagulation process improves the particle removal efficiency of mechanical air filters. If the aerodynamic diameter of particles formed by coagulation is greater than 1.0 μm, the air filter presents better removal efficiency[11]. Furthermore, combining ionizers with natural ventilation can greatly improve the removal of aerosol particles[14].

Ortiz-Grisales et al.[7] employed a high-voltage booster output to ionize air molecules from stainless steel electrodes, and the particle capture efficiency was as high as 97%. Two devices (5 cm × 40 cm acrylic chambers) were employed to produce 2.0×10^{13} ion/s, and $PM_{2.5}$ can be reduced from 999 mg/m^3 to 0 (in a 40 cm × 40 cm acrylic chamber) in about 5–7 min.

Pushpawela et al.[15] examined the particles removed when the ionizer was operated in a closed chamber with a volume of 1 m^3, a closed unventilated chamber with a volume of 20 m^3, and three forced ventilation chambers with volumes of 32, 45 and 132 m^3, respectively. The closed chamber experiment was conducted using ambient particles and smoke. While a small ionizer (Aironic AH-202, Aironic Pty Ltd., Australia) was used, 70% of the particles and smoke are removed within 15 min.

Shi et al.[16] evaluated the long-term particle collection efficiency of M6-level synthetic filters with and without ionization through field and indoor tests. Ionization treatment increased filtration efficiency by 40% during most operating time. The ionization system was managed by periodically switching the ionizer polarity and the filtration efficiency of aerosol particles was maintained above 50% for half a year. Compared with the F7-level filter, the pressure drop of the ionizer-assisted M6 filter was reduced by 25%–30%.

2.2 Decomposition mechanism of organic pollutants

The NAI active substances (ions or free radicals) play an important role in inducing the decomposition of indoor organic pollutants[8]. They can trigger a chain reaction and lead to fragmentation and ionization of indoor organic pollutants. Mass spectrometric monitoring of the intermediate shows that NAIs cause the alkyl groups to be cleaved and the alkyl radicals are subsequently replaced with negative electrons. Due to the high activity and selectivity of esters, a small reduction in CO_3^- can produce a large number of intermediates during the reaction with esters. Therefore, NAIs have a high degradation efficiency for a variety of esters. The real-time mass spectrometry analyses of intermediates reveal that the interactions between CO_3^- and O^- on aldehyde groups, alkyl oxidation and ·OH dehydrogenation, and alkyl cleavage are the three main pathways for the degradation of aldehydes, benzene congeners and esters.

3 Effects on Human Health

NAIs are recognized to improve mental health, productivity and overall well-being, but there is no consistent or reliable evidence for therapeutic effectiveness, and there is controversy regarding antimicrobial benefits[17].

3.1 Beneficial effects

The published studies on the beneficial effects of NAIs on human health are summarized in Table 2 (the case number + letter (a, b or c) indicates that the studies on the mechanism of action of NAIs are consistent across these studies). NAIs present beneficial effects on human health by improving the internal physiological processes of the human body, and disinfecting bacteria and inactivating viruses.

The beneficial effects of NAIs on human health are obtained by changing amino acid metabolism and promoting energy production[18], alleviating depression and atypical seasonal affective disorder (SAD) symptoms[19], benefiting cognitive function[20], improving respiratory function beneficial to heart rate variability[21-22], alleviating fatigue caused by muscle overload[23], being more effective for antidepressant efficacy[24], being efficacious in chronic depression[25], reducing depression in dozens of minutes[26], increasing sympathetic activity and improving cognitive ability[27], improving thermal comfort and human physiological stress[28], and so on.

The beneficial effects of NAIs in removing particles, disinfecting bacteria and inactivating viruses are multifaceted. These include enhancing deposition to reduce particulate concentration[29-31]; inhibiting microorganisms[17]; facilitating the removal of particles and viruses[32]; providing an energy-efficient air purification intervention[33]; offering better disinfection performance[10]; reducing the airborne *staphylococcus aureus* concentration[34]; removing contaminant particles[31], ultrafine particles[15], submicron particles[29], fog and smoke[30], and $PM_{2.5}$[35].

NAIs exert biological and therapeutic effects[36], with the possible mechanism playing biologically and physiologically essential roles such as biochemical reactions, transmembrane transport of a substance, and propagation of the nervous influx. There is also another point that NAIs affect the autonomic nervous system, increase sympathetic activity, and slightly decrease vagal efferent activity[27].

Table 2 Literature surveys on beneficial effect of NAIs on human health

Case number	Author	Study purpose	Study model	Study object	Ion concentration/ (ion/cm^3)	Primary outcomes of interest
1a	Kolarž et al.[32]	Effects of NAIs enhanced deposition on removal of aerosolized pathogens from indoor air	Control trial	Atomized NaCl solution aerosol and cigarette smoke aerosol	$C_{NAI}=2.0\times10^4$	Benefit particle removal such as viruses
1b	Sahay et al.[34]	Effects of NAIs and PAIs on building contaminants	Laboratory experiment	*Staphylococcus aureus*, VOCs, $PM_{2.5}$, etc.	$C_{NAI}=5.9\times10^4$ $C_{PAI}=9.2\times10^4$	Effective in reducing indoor microbes and particulate pollutants
2	Duan et al.[33]	Effects of air purification interventions on dosage delivered to small airway	Full-scale experiment using an *in vitro* airway model	3D-printed human replica (healthy 34-year-old male)	$C_{NAI}=1.5\times10^5$, 3.0×10^5 and 7.0×10^5, respectively	Effective in reducing small airway particle exposure
3	Shiue et al.[31]	Contaminant particle removal by ionizer	Closed test chamber	Different distances (30, 50, 70, and 90 cm) from the ionizer	$C_{NAI}=6.0\times10^5$	Particle removal efficiency was affected by particle size (0.1–0.5 μm)
4	Wu et al.[29]	Deposition removal of submicron particles by ionizer	Stainless steel test chamber	Air velocity of 0.56, 1.20 and 2.00 m/s, and NaCl particles of 30, 50, 100, 170 and 300 nm	$C_{NAI}=1.2\times10^6$–4.3×10^6	Air cleaner effectiveness ranged from 57.6% to 96.0%
5	Sawant et al.[30]	Effects of NAIs on fog and smoke	Closed dark room	Fog and vehicle smoke under natural decay or with NAI application	$C_{NAI}=5.0\times10^5$–2.0×10^7	93.0% to 97.0% of particles were removed in glass container
6	Pushpawela et al.[15]	Efficiency of ionizer in removing airborne particles	Chambers or rooms with volume of 1, 20, 32, 45 and 132 m^3	Controlled amount of smoke	$C_{NAI}=1.0\times10^6$	70.0% of particles were removed by ionizer in 15 min
7	Liu et al.[35]	Effects of NAIs on cardiorespiratory health	Randomized crossover trial	56 healthy college students (33 males and 23 females)	True purifier: 60 591±12 184; sham purifier: 53 ± 16	Effective in reducing indoor $PM_{2.5}$ concentrations and increasing NAI levels
8a	Jiang et al.[17]	Effects on humans, animals and microorganisms	Systematic review of studies on NAIs	263 studies (1960–2018)	$C_{NAI}>1000$	Benefit humans and animals, and inhibit microorganisms
8b	Nunayon et al.[10]	Air ion disinfection efficacy under different ventilation duct conditions	Steel ventilation duct system	Three bacteria species: *Escherichia coli*, *Salmonella typhimurium* and *Staphylococcus epidermidis*	$C_{NAI}=7.5\times10^5$–9.5×10^5; $C_{PAI}=7.5\times10^5$–9.5×10^5	Positive ionizer showed better disinfection performance
9	Bowers et al.[19]	Effects on depression and symptoms of SAD	Parallel-group design; single-blind study	40 subjects with symptoms of seasonal affective disorder	$C_{NAI}=2.0\times10^3$–2.0×10^6	Alleviate atypical SAD symptoms
10	Bowers et al.[19]	Effects on depression and symptoms of SAD	Parallel-group design; single-blind study	40 subjects with symptoms of seasonal affective disorder	$C_{NAI}=2.0\times10^3$–2.0×10^6	Alleviate depression

(Table 2 continued)

Case number	Author	Study purpose	Study model	Study object	Ion concentration/ (ion/cm^3)	Primary outcomes of interest
11a	Flory et al.[24]	Evaluating the antidepressant efficacy of two active treatments	Randomized controlled trial	73 female students and staff (18–51 years)	$C_{NAI}=4.0\times10^3–2.0\times10^6$	High-density NAIs have better antidepressant effects
11b	Goel et al.[25]	Effects on non-seasonal chronic depression	Randomized controlled trial	32 patients (8 males and 24 females)	C_{NAI} of high-density: 4.5×10^{14}; C_{NAI} of low-density: 1.7×10^{11}	Alleviate chronic depression
11c	Goel et al.[26]	Effects on mood changes in a student population	Subjects were randomly assigned to one of four conditions	118 subjects (49 males and 69 females)	C_{NAI} of high-density: 4.5×10^{14}; C_{NAI} of low-density: 1.7×10^{11}	Alleviate depression within 15–30 min
12	Perez et al.[36]	Effects on mood and depression	Meta-analysis model	33 studies (1957–2012)	$C_{NAI}=1.0\times10^3–2.75\times10^7$	NAIs at the highest level present lower depression scores
13a	Chu et al.[20]	Effects on cognitive function	Controlled test	39 non-smoking healthy adults (28 males and 11 females)	$C_{NAI}=1\,489.30\pm148.92$	Benefit cognitive function
13b	Xiao et al.[18]	Associations between NAI concentration and health effects	Analysis of 14 English-language studies	187 studies (2013–2023)	—	Benefit health by altering amino acid metabolism and promoting energy production
13c	Enache et al.[2]	Effects on living organisms	Environmental determinations	—	Town: < 500; extra-urban areas: 500–1500; modern office: 100–350	Promote environmental friendliness and offer additional therapeutic benefits
14	Wallner et al.[27]	Effects on cognitive performance, well-being, lung function and cardiovascular function	Double-blind cross-over trial	20 healthy non-smoking adults (10 males and 10 females)	$C_{NAI}=367–866$	Improve cognitive ability
15	Wallner et al.[27]	Effects on cognitive performance, well-being, lung function and cardiovascular function	Double-blind cross-over trial	20 healthy non-smoking adults (10 males and 10 females)	$C_{NAI}=367–866$	Increase sympathetic activity
16	Ho et al.[23]	Effects on the functional activities of badminton athletes	Double-blind study	38 badminton players (20 males and 18 females)	$C_{NAI}=0$, 300, 3 000 and 30 000, respectively	Alleviate fatigue caused by muscle overload
17	Liu et al.[21]	Associations between short-term exposure to forest NAIs and heart rate variability	Repeated-measure panel study	31 healthy adults	C_{NAI} of the median (IQR): 68.11 (138.20)	Improve HRV, especially to parasympathetic nerve activity
18	Liu et al.[22]	Associations between NAIs and cardiorespiratory effect after purification	Randomized, double-blind crossover study	44 healthy middle school students (24 boys and 20 girls)	$C_{NAI}=1.2\times10^4$	Improve respiratory function

Notes: HRV—heart rate variability; IQR—interquartile range; VOCs—volatile organic compounds.

3.2 Unavailing effects

The published studies on the unavailing effects of NAIs on human health are summarized in Table 3. The ionizer (NAI concentration is 997 ion/cm^3) could elicit significant benefits to the respiratory system, but is seemingly offset by apparently negative effects on cardiac autonomic function[37]. Figure 1 illustrates the effect of NAIs on human health summarized from the published literature. NAIs seem to have no influence (NAI concentration is 2 194 ion/cm^3 or 1 038 ion/cm^3) on lung health or function[27], unobvious effect (NAI concentration is $1.6\times 10^3 - 1.5\times 10^6$ ion/cm^3) on respiratory function and symptoms[38], no effect (NAI concentration is $(2.2\pm 0.3)\times 10^5$ ion/cm^3) on aerobic metabolism, performance or recovery during exercise[39], and no effect (NAI concentration is 7.0×10^6 ion/cm^3) on rat health about reproductive function or postnatal growth and development[40]. Ozone and electroporation, more than NAIs, are the principal causes of cell death amongst the bacteria[41]. If the unipolarity coefficient K is above 1.0, in combination with air pollution, NAIs might cause even more harm to the human body[12].

Table 3 Literature surveys on unavailing effect of NAIs on human health

Case number	Author	Study purpose	Study model	Study object	NAI concentration/ (ion/cm^3)	Primary outcomes of interest
19	Dong et al.[37]	Effects on children	Randomized and double-blind crossover study	44 healthy middle school students (24 boys and 20 girls)	Real-purification: 12 997 ± 3 814; sham-purification: 12 ± 10	Benefit respiratory system were offset by apparently negative effects on cardiac autonomic function
20	Alexander et al.[38]	Effects on respiratory function and symptoms	Literature review on random effects meta-analysis model	23 studies (1933–1993)	$1.6\times 10^3-1.5\times 10^6$	Unobvious effect
21	Nimmerichter et al.[39]	Effects on oxygen uptake kinetics, recovery and performance during exercise	Randomized and double-blind trial	14 trained males	Control group: $1.4\times 10^6-1.6\times 10^6$; indoor air: $(2.2\pm 0.3)\times 10^5$	No effect on aerobic metabolism, performance or recovery during exercise

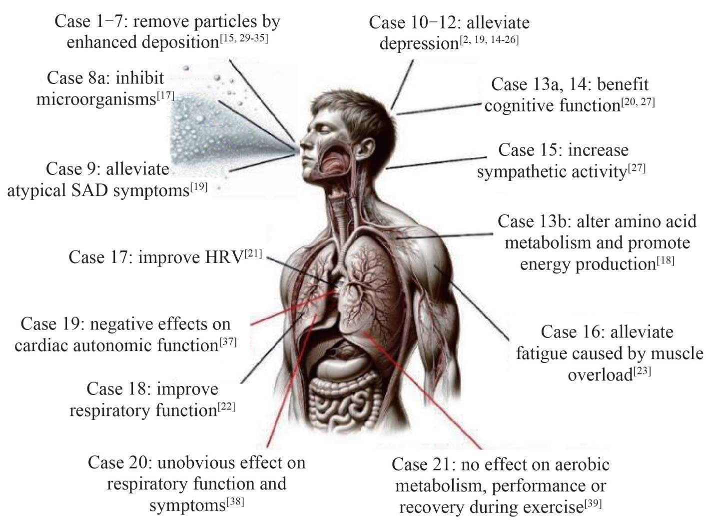


Fig. 1 Effect of NAIs on human health summarized from published literature

Although electrostatic precipitators and ionizers can do the same as high-efficiency particulate air (HEPA) in removing $PM_{2.5}$, both of them also generate by-products that might be harmful to human health[35]. An obvious disadvantage of ionizers is the emission of ozone[42-43], which can seriously harm our health with long-term exposure. Many ionizers emit ozone more or less[44-46]. At high humidity and voltage, for example, a humidity of 90% and a voltage of −7 kV, the ionizers should strictly comply with the electrostatic air purifier safety standards, Underwriters Laboratories, Inc. (UL, Northbrook, IL, USA) Standard 867 (UL—867)[47-48] and the 0.05 mg/L ozone limit specified by the State of California, USA[49].

Another side effect is that the continuous emission of NAIs into a closed environment can cause charges to build up on the insulating surface, which can then lead to static problems, especially at low humidity[50].

4 Discussion and Measures

In most natural environments[2, 51-52], NAI concentrations mainly range from 2.0×10^2 ion/cm^3 to 5.0×10^4 ion/cm^3. High-density NAI concentrations are commonly found alongside low-density particulate pollutants in natural environments. This clean and favorable air quality provides a beneficial bioactive capacity for human health.

4.1 Concentration distribution of NAIs on human health

Summarized from published literature, the full-scale and the partial-scale concentration distributions of NAIs on human health are shown in Fig. 2 and Fig. 3, respectively. Full-scale concentration distribution represents the inclusion of all the NAI concentrations involved in the cases, aiming to showcase the NAI concentrations studied in each case and their corresponding effects. Partial-scale concentration distribution primarily displays the cases that fall within the range of NAI concentrations in natural environments, with the maximum value on its horizontal axis equal to the highest concentration of NAIs found in nature.

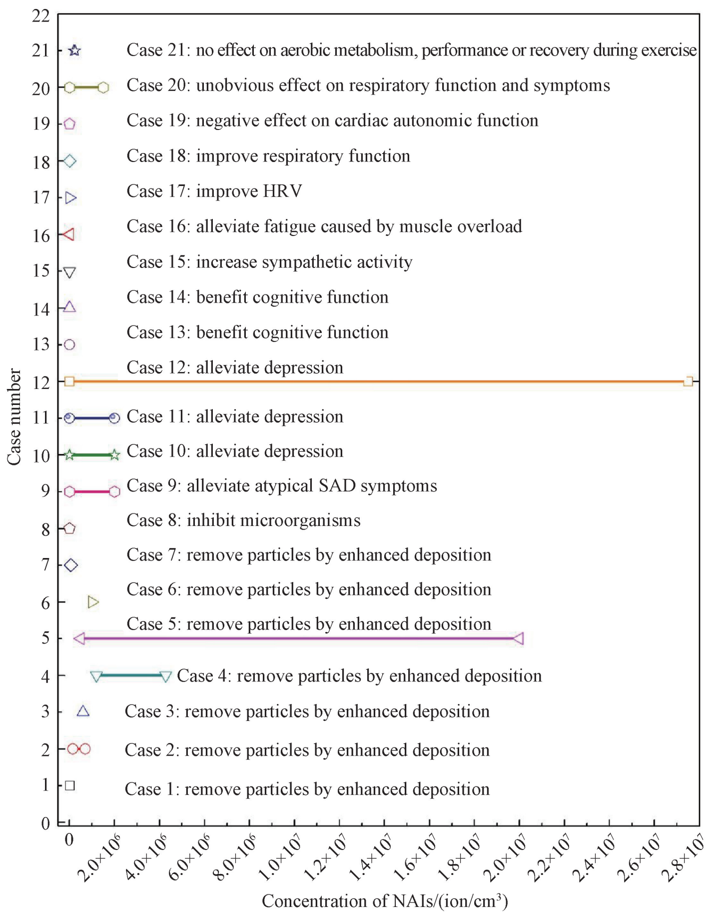


Fig. 2 Full-scale concentration distribution of NAIs on human health summarized from published literature

Out of the 18 cases demonstrating beneficial effects, six cases including Cases 4–5 (remove particles by enhanced deposition), Case 9 (alleviate atypical SAD symptoms), and Cases 10–12 (alleviate depression), explored NAI concentrations that either included 2.0×10^6 ion/cm^3 within the tested range, or reached this value as the maximum concerntration. The other 12 cases investigated the NAI concentrations that were lower than 2.0×10^6 ion/cm^3. For the three unavailing effect cases (Cases 19–21), their NAI concentrations are all below 2.0×10^6 ion/cm^3.

As illustrated in Fig. 3, the NAI concentrations of all partial-scale cases are larger than 2.0×10^2 ion/cm^3. Also, the NAI concentrations of nine cases including Case 1, Case 8, and Cases 13–19, are less than 5.0×10^4 ion/cm^3.

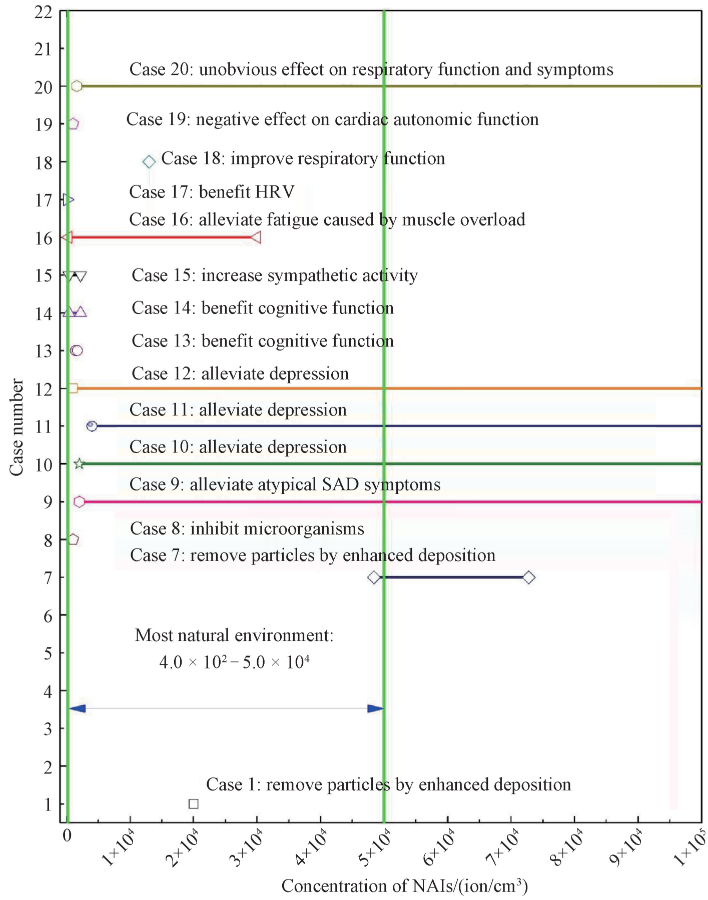


Fig. 3 Partial-scale concentration distribution of NAIs on human health summarized from published literature

Although some cases reported that higher NAI concentrations can provide more effectiveness, no case explores the full-size NAI concentrations for their beneficial or unavailing effect on human health. The relatively higher NAI concentrations seem to present lower depression scores[36], greater antidepressant efficacy[24], and efficacious in chronic depression[25]. However, the increase in NAI concentrations might elevate the levels of systemic oxidative stress[35]. To avoid adverse effects on human health, all cases seem to select serious and conservative levels of NAI concentrations. Further research is needed to explore whether increasing NAI concentrations beyond current levels could potentially enhance their beneficial effects on human health while ensuring safety.

4.2 Measures to balance beneficial and unavailing effects

Using ionizers as an alternative for enhancing indoor air quality presents certain risks and benefits. Risks include potential respiratory problems due to ozone production by ionizers and a rise in systemic oxidative stress levels that counteract the positive effects on cardiorespiratory function from reduced $PM_{2.5}$. The benefits of using air ionizers encompass air purification through the adsorption of fine particles such as dust, bacteria and viruses, along with alleviating depression and atypical SAD symptoms through increased NAI concentrations.

To balance the beneficial and unavailing effects of NAIs, a more extensive and comprehensive scientific investigation should be conducted before employing ionizers as alternative solutions to improve indoor air quality. Taking the enclosed environment as an example, the measures are in the following steps.

1) The type and concentration of particulate pollutants should be generally assessed in advance. This is primarily due to the potential ion-particle interactions between NAIs and particulate pollutants. Furthermore, if ionizers are effective in removing particulate pollutants from the air, the parameters for ionizers need to be adjusted. They no longer represent pure NAI exposure but instead reflect a modified environment where particulate pollutants have been diminished. The coexistence of NAIs with particulate pollutants and gases[12] (such as CO, NO_x and SO_2) in indoor air may expose occupants to a potentially harmful combination.

2) The selection of ionizers should focus on a few variables that impact the ion concentration, such as the air circulation rate, relative humidity and wall electrostatic characteristics (prevent charging insulating surfaces).

3) The regulation of NAI concentration should be

moderated to ensure safety and efficacy, with adjustments based on specific conditions. This can be accomplished through monitoring NAI levels, modulating ionizer output, and managing operation time, thereby minimizing the production of by-products.

4) The immediate implementation of emergency procedures for ionizers, including discontinuing their use or switching them off, should take place as soon as any individual experiences discomfort or adverse effects.

5 Conclusions

Based on the survey of published literature, this study highlights the mechanism of NAIs for improving the indoor air environment, the beneficial or unavailing effects on human health, and alternative measures to balance beneficial and unavailing effects. The conclusions are drawn in the following three points.

1) Consensus effect of NAIs on human health. There is common consent that NAIs can remove particles by enhanced deposition, inhibit microorganisms, alleviate depression, benefit cognitive function, and even increase sympathetic activity.

2) Contradictory effect of NAIs on human health. Some studies advocate that forest NAIs are beneficial to heart rate variability, but others claim that there are negative effects on cardiac autonomic function. Also, some studies report that NAIs can improve respiratory function, but others elaborate that there are unobvious effects on respiratory function or no effects on aerobic metabolism performance or recovery during exercise. These discrepancies may be caused by differences in research methods and sample selection. The effects of NAIs in forests on human health are inconsistent in some studies, and such differences should be understood and explained from objective and scientific perspectives. Thus, more studies should be further investigated on the effects of NAIs on human health.

3) Desirable NAI concentrations. There is no extensive or complete investigation of the influence of NAI concentrations on human health. This means that there is a lack of sufficient evidence to support the unavailing NAI effects on human health, to provide a full-scale response curve of NAI concentrations on human health, or to maintain moderate NAI concentrations in certain types of indoor environments or for specific occupants. However, the World Health Organization (WHO) considers the air with NAI concentrations between 1 000 ion/cm^3 and 1 500 ion/cm^3 to be clean air[53]. Some studies have revealed that NAI concentrations above 700 ion/cm^3 could meet the basic physiological needs of the human body, while NAI concentrations above 1 000 ion/cm^3 could benefit human health[54]. As mentioned earlier, NAI concentrations in most natural environments range from 2.0×10^2 ion/cm^3 to 5.0×10^4 ion/cm^3. The desirable range of NAI concentration is recommended to be 1.0×10^2–5.0×10^4 ion/cm^3, which is a noteworthy advancement.

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室内环境空气负离子对人体健康的功效及浓度分布

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摘　要：室内环境中存在的空气负离子（negative air ion，NAI）可有效减少微粒污染物和气体污染物，并抑制微生物、细菌和病毒的生长，从而对人体健康产生积极影响。该综述调查了不同模块类型的常见离子发生器，分析了 NAI 改善室内空气质量的机制及 NAI 对人体健康的影响。研究还调查了不同的 NAI 浓度对人体健康各方面的影响，以及平衡有益和不确定影响的替代措施。虽然 NAI 在去除颗粒物、缓解抑郁、增强认知功能甚至刺激交感神经活动方面具有功效，但在对心脏自律神经功能和呼吸生理的影响方面，存在着相互矛盾的研究结果。为解决这一复杂问题，需考虑采取其他措施，在 NAI 的有益影响和不确定影响之间取得平衡。这些措施包括对颗粒污染物特性的总体评估，对 NAI 发生器的选择，以及遵守所推荐的 NAI 最佳浓度阈值。

关键词：室内环境；空气负离子；人体健康；颗粒去除；替代措施