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Energy Consumption Landscape and Mitigation Strategies for Carbon Emissions in Biosafety Laboratories

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ABSTRACT

Biosafety laboratories are essential facilities for life science research. To maintain the stability of internal environmental parameters such as temperature and humidity, pressure differentials, and cleanliness, their energy consumption is significantly higher than that of conventional civilian buildings. This paper summarizes biosafety laboratories' current energy consumption status and analyzes key factors influencing their energy use, including air change rates, pressure control, airflow organization, and air treatment. Furthermore, it proposes general and specific energy-saving measures for different biosafety laboratory levels. Finally, recommendations are provided for the future construction and development of biosafety laboratories.

Keywords: Biosafety laboratories, HVAC, Energy efficiency, Carbon reduction, Energy consumption

NONMENCLATURE

Abbreviations	
ACH	Air changes per hour
AHU	Air handling unit
BSC	Biological safety cabinet
BSL	Biosafety Laboratory

1. INTRODUCTION

Biosafety Laboratory (BSL) is a special building place for scientific research, according to the degree of biohazard of the object to be handled and the protective measures to be taken, biosafety laboratories can be categorized into four levels (GB 50346-2011 Biosafety Laboratory Building Technical Specifications, 2012), of which the third and fourth level biosafety laboratories are called high-level biosafety laboratories(Yanguo Zhang & Qu, 2018), and each level of biosafety laboratory's main differences are shown in 错误!未找到引用源。. Since the research object of BSL-1 is non-hazardous or low hazardous, it can be regarded as an ordinary laboratory. The research object of BSL-2 may be pathogenic to humans or animals, and tends to be a separate room with controlled access.BSL-3 and BSL-4 are classified as separate controlled areas to maintain negative pressure due to the higher pathogenicity of the pathogenic microbial factors under study.BSL-4 is even used as a specialized building, completely isolated from the outside world.

Since the SARS incident, China has gradually established a basically perfect management system for biosafety laboratories, and at present, there are 63 high-grade biosafety laboratories and 46,000 BSL-2(National Health Commission of the People's Republic of China), and the scale of biosafety laboratories has gradually increased. Compared with traditional buildings, biosafety laboratories have higher requirements in terms of temperature and humidity, cleanliness, and the number of air changes.

However, with the increase in the number of biosafety laboratories, the problem of high energy consumption and high carbon emission has become increasingly prominent. A study shows(Qiu, Weng, Jiang, Yan, & Gu, 2019) that 64.03% of the BSL-2 in Zhejiang Province are medical institutions, and 22.08% are distributed in the Centers for Disease Control and Prevention (CDC), due to the need to maintain good ventilation, as well as to maintain a variety of high-energy-consuming equipment in continuous operation, resulting in high energy consumption of laboratories, which is one of the reasons for the high energy consumption of buildings in the field of medical care and public health. Data show(National Renewable Energy Lab. (NREL), Golden, CO (United States), 2008a) that the annual energy consumption of biosafety laboratories is about 5-10 times higher than that of ordinary office buildings, and for general laboratories (BSL-1/2), most of the energy consumption comes from the power consumption of incubators, refrigerators, ultrasonic cleaners, centrifuges, and other experimental

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instruments, as well as computers, lighting equipment, and so on. Typically, the electrical energy consumption (socket load) of a general office building is 5.38 - 10.76 W/m^2 (after unit conversion), while that of a laboratory building is 21.53 - 215.28 W/m^2. About 24% of BSL-3 laboratories in China are not functioning properly due to the huge energy consumption(X. Liu, Li, Rong, Zhao, & Wang, 2014), which results in insufficient operating funds.

The U.S. established the U.S. Green Building Council (USGBC) in 1993 and first proposed planning guidelines for laboratory buildings in 2005(J. Lee & Schuetze, 2012). Subsequently, Germany, the United Kingdom, Canada and other countries have also introduced relevant policies to promote the green development of various laboratories, including biosafety laboratories. The U.S. has also launched the "Laboratories for the 21st Century" (Labs21) program, established the International Institute for Sustainable Laboratories (I^{2}SL), and conducted a survey on more than 800 buildings(I^{2}SL, 2020), and among the laboratory buildings surveyed, those with biosafety laboratories are the ones that have the most biosafety laboratories. Of the laboratory buildings surveyed, those with biosafety laboratories consume an average of more than 1000 kWh/m^2 per year, compared to the average office building in the United States, which consumes only about 160 kWh/m^2 per year(He, Hii, Wong, & Peck, 2022).

Table 1. Key differences between biosafety laboratories of different levels

Characteristics	BSL-1	BSL-2	BSL-3	BSL-4
Research subjects	Non-hazardous or low-hazard microorganisms (non-pathogenic or extremely low pathogenicity)	Moderate hazard microorganisms (may cause disease in humans or animals, but treatment is usually available)	Highly hazardous microorganisms (airborne, potentially causing serious illness)	Deadly pathogens (usually without vaccines or effective treatments)
Representative pathogens	Escherichia coli (E. coli K-12), Bacillus subtilis	Hepatitis B virus (HBV), influenza virus, Salmonella	Mycobacterium tuberculosis, SARS-CoV-2, Bacillus anthracis	Ebola virus, Marburg virus, Lassa fever virus
Personal protection	Basic laboratory clothing	Gloves, goggles, lab coats	N95 masks or full-face respirators, dedicated lab coats	Positive pressure protective clothing, independent air supply system
Laboratory location	Ordinary laboratory	Separate room, controlled access	Controlled areas, negative pressure environment	Specialized buildings, complete isolation
Air control requirements	No special requirements	Biological safety cabinet (BSC-2) for aerosol-generating experiments	Negative pressure ventilation system, air filtration (HEPA filtration)	Sealed system, double HEPA filtration, airtight doors
Waste disposal	Routine handling	Autoclaving	High-pressure sterilization post-treatment	High-temperature, high-pressure sterilization, special waste disposal

With the introduction of the "dual-carbon" goal, the concept of green development is becoming more and more important, and the realization of carbon neutrality is a common challenge facing the human society at present(Zhu, Wang, & Han, 2023). In December 2021, the National Development and Reform Commission issued the "14th Five-Year Plan" (Development and Reform High Technology [2021] No. 1850), which points out that it is necessary to strengthen the scientific and technological support for biosafety risk prevention and control. Biological Economy Development Plan" (Development and Reform High Technology [2021] No. 1850), pointing out that it is necessary to strengthen the scientific and technological support for biosafety risk prevention and control. Therefore, biosafety needs to be ensured as a prerequisite to balance the relationship between risk assessment and laboratory energy consumption.

In order to keep abreast of the current research progress on energy saving and carbon reduction in biosafety laboratories, this paper summarizes the current situation of energy consumption in biosafety laboratories, analyzes the main factors affecting energy consumption in laboratories, and proposes energy saving and carbon reduction strategies for biosafety laboratories of different grades from the perspectives of general and specific measures, with a view to providing new perspectives to the users and researchers of biosafety laboratories.

2. STATUS OF ENERGY CONSUMPTION

The energy consumption of the ventilation system of a biosafety laboratory is an important part of the energy consumption of the whole laboratory, and the energy consumption of the ventilation system mainly comes from the power consumption of the airflow (fans, filters, piping systems, etc.) and air treatment. The main factors affecting power consumption are the number of air changes in the laboratory, pressure control and airflow organization, etc. Air treatment energy consumption is mainly caused by heating, cooling and filtering gas.

2.1 Air changes per hour (ACH)

Ventilation rate usually refers to the volume of fresh air entering or leaving the room per unit of time, the unit is usually cubic meters per hour (m^3/h) or liters per second (L/s), the number of air changes is the number of times the indoor air has been completely replaced per unit of time, which is obtained by dividing the ventilation rate by the volume of the room.

Research shows(Deng, Feng, & Cao, 2018; Jin, Memarzadeh, Lee, & Chen, 2012; Klein, King, & Kosior, 2009; Stuart, Sweet, & Batchelder, 2015) that the energy consumption of a biosafety laboratory is linearly and positively correlated with the ACH, but the ACH is not the higher the better, blindly increasing the ACH will aggravate the load of the ventilation system, and the energy consumption and cost required to maintain the operation of the equipment will be increased, and there is a possibility of lowering the safety conditions of experimental research, such as the laboratory's specific The optimal ACH for BSL-3 should be controlled in the range of 10~20 according to the demand. For specific engineering practice, the ACH required should be reasonably determined according to the functional use of each room in the biosafety laboratory, so as to reduce the ventilation load.

In order to explore the requirements for the number of air changes in different levels of biosafety laboratories, this paper is summarized after combing through literature, and the results are shown in 错误!未找到引用源。. The minimum ACH varies among different safety level laboratories: BSL-1/ABSL-1 usually allows windows to be opened, so the ACH is low (no specific requirements under conditions where windows can be opened); BSL-2/ABSL-2 also allows windows to be opened, but requires ≥ 6 ACH in controlled environments; BSL-3/ABSL-3 usually requires 15 ACH and above, emphasizing air flow control to minimize the risk of contamination; BSL- 4/ABSL-4 require more ACH, usually 15 or more, and in some cases ≥ 12.

Table 2. Required ACH for biosafety laboratories according to various sources

GB 50346-2011 "Biosafety Laboratory Building Technical Specifications"		
Level/Room		Minimum ACH
BSL-1/ABSL-1		Operable Window
BSL-2/ABSL-2 Type A and B1		Operable Window
BSL-2/ABSL-2 Type B2		12
BSL-3/ABSL-3		15 or 12
BSL-4/ABSL-4		15 or 12
BSL-3 and BSL-4	Main Laboratory Clean Corridor	15 or 12
	Isolation Corridor	15 or 12
	Preparation Room	15 or 12
	PPE Change Room	10
	Shower Room within Protective Zone	10
	Shower Room outside Non-Protective Zone	/
	Chemical Shower Room	4
	ABSL-4 Animal Cadaver Waste Treatment Room and Protective Zone Water Treatment Room	4
	Clean Garment Change Room	/

NIH Design Requirements Manual (Rev. 1.5)	
Level/Room	Minimum ACH
BSL-1/ABSL-1	/
BSL-2/ABSL-2	/
Laboratory[I]	6
Surgical Scrub Room[I]	10
Animal Cadaver Decontamination Room[I]	15
Adult Room[I]	6
Office Space[I]	6
Operating Room[I]	20
Equipment Storage Room[I]	6
Post-Mortem Recovery Room[I]	10
Animal Preparation Room[I]	10
BSL-3	6
ABSL-3	10-15
BSL-4/ABSL-4	/

Guidelines for Safe Laboratory Design		
Design Objective	8-10 (occupied)	
	4-6 (unoccupied)	
Lab Ventilation ACH Rates Standards and Guidelines		
European Standard DIN 1946-7 - General Laboratory	25 m^3/hr./m^2	9.1[II]
		8.2[II]
University of Cambridge Research - Chemical Operations	6-8 is best; ≥12 is not necessary	
Guidelines for Laboratory Design: Health, Safety, and Environmental Considerations, Fourth Edition		
Level/Room	Minimum ACH	
Standard Dissection Laboratory[III]	15-20	
General Storage Room[III]	15-20 (can be appropriately reduced when unoccupied)	
Chemical Storage Room	6	
BSL-3/ABSL-3	/	
BSL-4/ABSL-4	/	

Ⅰ. Laboratories classified as animal research facilities by the National Institutes of Health (NIH) also possess characteristics of biosafety laboratories.
Ⅱ. DIN 1946-7 recommends a minimum ventilation rate of 25 m^3/hr./m^2 for general laboratories. This corresponds to an ACH of 9.1 for a laboratory with a height of 9 feet (2.74 meters) and 8.2 for a laboratory with a height of 10 feet (3.05 meters).
Ⅲ. According to the National Association of Medical Examiners (NAME, 2009), most standard autopsy and morgue facilities are designed as BSL-2 laboratories. Standard autopsy laboratories are used for handling general cadavers. Special autopsy laboratories are designated for handling cadavers with acute infectious agents or those carrying Biosafety Level 2 and Level 3 pathogenic agents.

Different international standards are broadly consistent in ACH requirements, emphasizing air flow control and contamination protection in biosafety laboratories, with lower air change requirements for general laboratories (BSL-1/2), and some standards allowing lower ACH counts to save energy, whereas animal biosafety laboratories (ABSL) usually require more stringent air control, especially in animal surgery and body handling equipment areas. For high level biosafety laboratories, a high ACH is usually required to ensure safety, but this also results in higher energy consumption, therefore, international standards usually recommend no more than 12 to minimize energy wastage while ensuring safety.

A study(Tan & Cao, 2021) investigated the ACH in 98 core workspaces in 28 BSL-3 in China, more than half of the core workspaces had 15-30 ACH, and more than 1/4 of the core workspaces had more than 30 ACH, which was significantly higher than the indexes stipulated in the Technical Code for Biosafety Laboratory Construction of GB 50346-2011.

2.2 Pressure control

For high-level biosafety laboratories, in order to prevent the leakage of internal hazardous factors, to protect laboratory personnel from the risk of exposure, and at the same time to meet the specific experimental requirements, it is necessary to maintain a stable negative-pressure environment inside the laboratory. The specific principles of maintaining negative pressure refer to the following formula:

$$Q_S = Q_F + Q_R \tag{1}$$

$$Q_S + Q_L = Q_E + Q_R \tag{2}$$

Equation (1) minus (2) is obtained:

$$Q_L = Q_E - Q_F \tag{2}$$

Where Q_S is the supply air volume, Q_F is the fresh air volume, Q_R is the return air volume, Q_L is the increase in exhaust air volume due to negative pressure infiltration, and Q_E is the exhaust air volume.

According to equation (3), if the difference between the total exhaust air volume and the total fresh air volume is greater than 0 (i.e., $Q_L > 0$), the isolation area of the laboratory can maintain an absolute negative pressure, and the system reaches dynamic equilibrium at this point when the Q_L value is constant(Liang, Feng, & Li, 2020). In order to maintain the dynamic equilibrium of the negative pressure, the laboratory needs to continuously extract the room air by means of a specialized ventilation system (fans), which leads to a dramatic increase in the energy consumption of the ventilation system(Perazzo Pedroso Barbosa & de Carvalho Lobo Brum, 2017). **错误!未找到引用源。** summarizes the disturbing factors and the intensity of influence on the environmental pressure in biosafety laboratories. Usually, in high-grade biosafety laboratories, in addition to the leakage from the door gap, the opening and closing of the door, the start and stopping of the supply and exhaust fans, and the start and stopping of the biosafety cabinets cause damage to the stability of the air flow rate (the dynamic balance of the negative pressure)
in the laboratories, especially in the high-grade biosafety laboratories, which affects the pressure control(Liang et al., 2020; S. Liu et al., 2006; National Renewable Energy Lab. (NREL), Golden, CO (United States), 2008a, 2008b; PhD, Tay), resulting in additional energy consumption.

No.	Interference Factors	Impact Intensity
1	Increase or decrease in duct system resistance (filter clogging after a period of operation)	Slow speed, not significant change, easy to control
2	Opening or closing of doors (with dampers)	Slow speed, not significant change, easy to control
3	Opening or closing of doors (without dampers)	Fast impact speed in this area, significant change, difficult to control
4	Start or stop of biological safety cabinets	Fast impact speed in this area, significant change, difficult to control
5	Start or stop of supply and exhaust fans	Fast speed, significant change, difficult to control
6	Closing valves due to sterilization operations	Fast speed, significant change, difficult to control

Research shows(Hong & Park, 2012; Hwang, Bum, & Hong, 2014; H. W. Lee, choi, & Kwan, 2009; Park & Hong, 2010) that, on the basis of meeting the sealing of the laboratory door and the infiltration air volume, by regulating the air supply and exhaust system in each functional space of the laboratory by area, the energy consumption of the laboratory as well as the diffusion of gaseous pollutants can be effectively reduced; maintaining a stable differential pressure can effectively reduce the initial investment in the air supply and exhaust system; for the biosafety cabinets, removing the necessary start-stop energy consumption can also play a significant role in energy saving. For biosafety cabinets, in addition to the necessary start and stop energy consumption, if you can use the heat recovery ventilator (Heat Recovery Ventilator, HRV) device to recover the waste heat of the exhaust air during operation, it can also play an obvious energy-saving effect. There are also studies to analyze the control methods and strategies for pressure fluctuations in biosafety laboratories(Bu, Wei, Xing, Tong, & Zhao, 2020; Cao, Wang, Li, & Gao, 2018; Liang, Cao, Li, Feng, & Wang, 2020; P. Liu, 2022; Z. Zhang, 2013), such as strictly controlling the start-up sequence and start-up intervals of the supply and exhaust fans, and using fast integrated variable air volume controllers to quickly respond to instantaneous pressure changes caused by door opening or exhaust fan failure, etc. These methods and strategies can precisely control the laboratory pressure, maintain safety while being able to save energy. These methods and strategies can precisely control the laboratory pressure and minimize energy waste while maintaining safety.

2.3 Air flow organization

Increasing ventilation rates has limited effect on airborne infection control in mixed ventilation modes(National Renewable Energy Lab. (NREL), Golden, CO (United States), 2008b; Perazzo Pedroso Barbosa & de Carvalho Lobo Brum, 2017), local airflow patterns are more important than overall ventilation rates, which means that optimizing the airflow organization reduces the overall ventilation rate, which in turn reduces the number of air changes, reduces the ventilation load, and reduces unnecessary energy waste, while ensuring safety.

Xu(Xu, Zhang, Zhang, & Yu, 2005) studied the three airflow organizations of up-feed-down-return, up-feed-up-return, and down-feed-up-return in the biosafety laboratories, and analyzed them from the aspects of the velocity field of the return air inlet, the velocity field of the supply air inlet, the following velocities, and the synthesis of velocities by numerical simulation, and concluded that the form of up-feed-down return is the only one that can rapidly press the gaseous pollutants generated in the biosafety laboratories towards the respiratory belt of the human body and the point of occurrence below, reducing the health risk of operators. Cao(Cao, Zhang, Xu, Yu, & Wen, 2006), Zhang(Yizhao Zhang, Yu, Cao, Xu, & Wen, 2006) and others have studied the organization of airflow in biosafety laboratories by means of simulations or experiments and reached the same conclusions. Another study also showed(Zhong et al., 2024) that the aerosol concentration of the top-fed top-exhaust is 1.4 times higher than the top-fed bottom-exhaust under the same conditions, and that by optimizing the ventilation parameters, the reduction of the air supply velocity from 1m/s to 0.8m/s can reduce the energy consumption of the laboratory by 15-30%.

2.4 Air Treatment

Some researchers have taken an animal biosafety laboratory as a research object(Li, Chen, & Chen, 2011), and simulated and analyzed its energy consumption behavior, and the results are shown in 错误!未找到引用源。. Heating and cooling energy consumption accounts for three-quarters of the energy consumption of the entire animal biosafety laboratory. Since the temperature and humidity set point has a great influence on the total annual load of heating and cooling(Tan, Cao, & Chen, 2020), the higher the indoor temperature and humidity set point in winter, the higher the heat load, and the humidification heat load used to maintain the relative humidity will also increase. Literature has shown(Cui, Liu, & Conger, 2006; Eades, 2018) that for air-handling units in heating and cooling systems, 13% of energy and 37% of water can be saved by reusing condensate and waste heat from the air-handling units, with significant potential for energy and water savings.

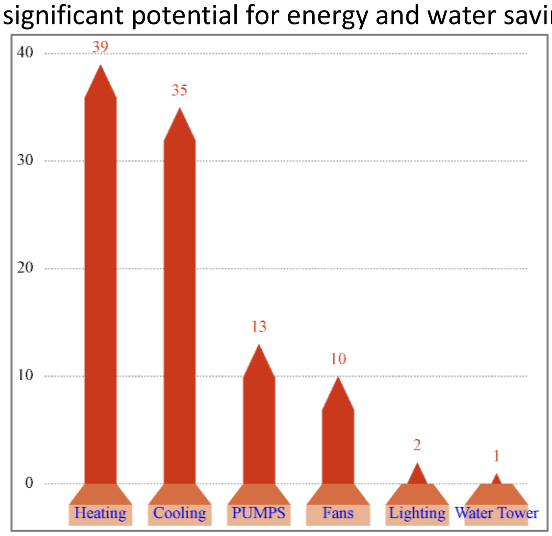

Figure 1. Energy Consumption Proportions of an Animal Biosafety Laboratory

Reducing energy consumption in heating and cooling systems of biosafety laboratories can be achieved through energy management. Jiang(Jiang et al., 2009) took a BSL-2 laboratory as the research object, combined with building automation technology, collected parameters such as heating capacity, supply and return water temperature, and circulating water volume, and visualized them to guide the management of the biosafety laboratory in making adjustments. The results showed that during a heating season, electricity consumption was reduced by approximately 35%, and heating quality was improved, demonstrating significant energy-saving effects. Additionally, by connecting through a smart gateway, the equipment within the biosafety laboratory can be integrated into an Internet of Things (IoT) platform capable of data analysis(Mahato, Yadav, Saxena, Pundir, & Mukherjee, 2018), enabling precise control of energy consumption by analyzing factors such as energy consumption, laboratory personnel occupancy rates, and equipment operation status.

3. ENERGY SAVING AND CARBON REDUCTION MEASURES

Since biosafety laboratories are classified into different levels, specific measures should be taken to reduce energy consumption for laboratories of different levels. For general laboratories (BSL-1/2), energy-saving measures commonly used in ordinary buildings can be adopted. For high-level biosafety laboratories (BSL-3/4), appropriate measures should be taken to reduce energy consumption while ensuring safety.

3.1 Generic measures

(1) Heating and air conditioning

Heating and air conditioning systems should clearly define zones and ensure that system divisions facilitate environmental control and energy metering during operation and maintenance, thereby reducing the workload of energy consumption data collection. The set operating temperature should not exceed (in winter) or fall below (in summer) the design value by more than 2°C. The outlet water temperature of the cooling equipment unit can be adjusted based on outdoor meteorological parameters and changes in dehumidification load. Ensure hydraulic balance and airflow balance in the heating and air conditioning system to avoid excessive consumption of water, electricity, and heat energy due to maintaining indoor temperature and pressure differentials, thereby reducing carbon emissions. Select heating and cooling source units compatible with locally available long-term fuel supplies. Locate the cooling plant or cooling units near the room with the highest cooling load to ensure adequate natural ventilation and insulation/cooling measures.

(2) Ventilation systems

Currently, the ventilation rates in most biosafety laboratories exceed the values specified in current standards. To promote energy conservation and carbon reduction, the ventilation rates in laboratories should be controlled to align with national standard indicators, preventing excessive ventilation rates. For general laboratories (BSL-1/2), natural ventilation should be used when it meets the environmental requirements of the laboratory. If natural ventilation cannot ensure cleanliness, pressure, or experimental process conditions, mechanical ventilation or a combination of natural and mechanical ventilation should be used. For laboratory equipment that generates significant heat and moisture, local exhaust ventilation should be installed. Exhaust ventilation within laboratories can be designed based on actual indoor and outdoor air parameters to establish energy-saving operation plans and procedures for exhaust energy recovery systems. When operating an exhaust energy recovery system, reasonable control strategies should be developed based on actual application conditions. If exhaust air contains potential contaminants, recovery methods that prevent cross-contamination of new exhaust air should be selected.

High-efficiency air handling units (AHUs), energy-efficient fans, and cooling equipment can also be selected; Utilize variable frequency control technology to automatically adjust the operating speed and power of air conditioning equipment according to the needs of the laboratory interior; employ heat exchangers and air recovery systems to recover thermal energy from exhaust gases emitted by equipment such as biosafety cabinets, autoclaves, and transfer chambers, which can be used for preheating or cooling incoming fresh air; implement proper thermal insulation design for laboratory buildings to reduce heat transfer and lower air conditioning loads.

(3) Management requirements

Biosafety laboratories should incorporate energy conservation and carbon reduction into their laboratory quality and safety management systems, establishing effective and feasible energy conservation and carbon reduction systems and procedures. When implementing carbon reduction measures, risks that may impact laboratory activity safety and quality should be identified. Following risk analysis and risk assessment, corresponding control measures should be implemented, and relevant emergency response plans should be developed as necessary. Regular energy conservation and carbon reduction training sessions should also be conducted to ensure that laboratory personnel in different roles understand the guidelines for energy conservation and carbon reduction and assume their respective responsibilities and obligations in their respective fields.

Define the responsibilities of the primary departments and relevant departments responsible for energy conservation and carbon reduction, clarify the duties, rights, and interrelationships of management, operational, or verification personnel, and ensure the implementation of carbon reduction management systems. Conduct regular reviews of energy conservation and carbon reduction efforts, analyze the causes of any non-conformities, and develop corresponding corrective measures. Additionally, energy conservation and carbon reduction management can be integrated into the information management system of biosafety laboratories to measure, monitor, and control environmental parameters in various functional rooms of the laboratory.

3.2 Specific measures

According to 错误!未找到引用源。, the safety requirements for biosafety laboratories of different levels vary, so in addition to general measures, specific measures must be taken to reduce energy consumption in accordance with specific requirements. BSL-1 laboratories handle harmless or low-risk biological materials and do not require special biosafety equipment, resulting in relatively lower energy consumption compared to other levels of laboratories. Therefore, the focus of energy conservation efforts is on daily energy-saving practices, primarily relying on the aforementioned general measures.

For BSL-2 laboratories, in addition to general measures, the energy efficiency of biological safety cabinets (BSCs) should be a key focus. According to a literature review by Lab Manager(PhD, Tay), traditional BSCs driven by AC motors convert excess current into heat, leading to energy waste and requiring additional energy for cooling. Therefore, BSL-2/3/4 laboratories should use more energy-efficient DC motors to ensure BSCs operate in low-flow mode, reducing energy waste while maintaining safety.

For BSL-3, in addition to adopting all energy-saving measures from BSL-2, further optimization of energy efficiency should be implemented for complex ventilation systems, such as using high-efficiency air filters and variable-speed drive fans, designing energy recovery systems to recover and recycle heat from BSC and duct exhaust gases, and improving energy efficiency(Bell, 2009). While ensuring experimental conditions and personnel safety, appropriately reduce the pressure differential of the ventilation system, control the air exchange rate, and reduce ventilation load. Additionally, energy-efficient automated equipment such as autoclaves and incubators should be used.

For BSL-4 facilities, in addition to implementing all energy-saving measures applicable to BSL-3, special attention should be given to the energy efficiency of positive-pressure protective clothing systems to ensure operator safety and prevent excessive pressure. The frequency and duration of airtight door use should be minimized to ensure the proper performance of seals.

4. CONCLUSION AND OUTLOOK

This research reviews the current energy-saving and carbon reduction efforts in biosafety laboratories through a literature review, analyzes the impact of air exchange rates, pressure control, airflow organization, and air handling on laboratory energy consumption, and proposes energy-saving and carbon reduction measures based on different laboratory grades. The conclusions are as follows:

The number of BSL-1/2 laboratories far exceeds that of BSL-3/4 laboratories, and energy consumption primarily stems from the continuous operation of laboratory instruments and equipment, with energy consumption approximately 5 – 10 times that of ordinary office buildings.

The air exchange rate in most high-level biosafety laboratories in China exceeds the recommended standard values. Under the premise of meeting cleanliness grade requirements, the air exchange rate can be appropriately reduced to conserve energy.

Strict control of laboratory pressure differentials is necessary to minimize airflow disturbances and maintain dynamic negative pressure balance.

Air handling within the laboratory is another factor contributing to high energy consumption, making reasonable temperature and humidity settings critically important.

While there are common energy-saving measures applicable to all levels of biosafety laboratories, specific measures tailored to their respective characteristics should be adopted to achieve energy conservation and carbon reduction.

The current GB 50346-2011 “Technical Specifications for the Construction of Biosafety Laboratories” contains few specific provisions regarding energy conservation and carbon reduction measures. International standards manuals, such as the U.S. “Biosafety in Microbiological and Biomedical Laboratories” (BMBL-6), include a separate section titled “Appendix L - Sustainability” which sets forth relevant requirements for the operation and management of biosafety laboratories. Chinese standards should also incorporate sustainability requirements for biosafety laboratories, using the mandatory nature of standards to drive Chinese biosafety laboratories toward energy conservation and carbon reduction.

In recent years, China has hosted academic forums such as the “International Forum on Environmental Control Technology for Scientific Laboratories” and the “High-Level Forum on Innovation and Development of Future Laboratories” and established the Laboratory Environmental Control Working Group under the Chinese Preventive Medicine Association's Health Engineering Committee. However, there remains a lack of specialized organizations dedicated to researching laboratory energy conservation. Due to the special nature of biosafety laboratories, laboratory personnel pay little attention to energy consumption and carbon emissions in such buildings, while building energy conservation professionals cannot enter the laboratories to conduct research. The coordination between different disciplines is inadequate, resulting in insufficient depth in the energy conservation and carbon reduction efforts of biosafety laboratories. It is urgent to establish a specialized institution or research society dedicated to energy conservation in biosafety laboratories to enhance communication and learning between laboratory staff and building energy conservation researchers. Government authorities or laboratory administrative departments could also issue relevant policies to support qualified building energy efficiency professionals in conducting on-site testing and research within biosafety laboratories, provided that laboratory operations and personnel safety are ensured. This would facilitate the collection of foundational data and the advancement of research efforts.

Looking ahead, smart biosafety laboratories can be developed using new technologies such as the Internet of Things, big data, and artificial intelligence to precisely control the instruments and equipment in each functional room of the biosafety laboratory, monitor their operational status, and achieve seamless integration, control, and efficient interaction between security and fire protection, lighting, access control, and other systems, thereby realizing smart management and reducing the laboratory's energy consumption and carbon emissions. Develop intelligent robots tailored for biosafety laboratories to assist laboratory personnel in performing certain experimental operations, thereby improving experimental efficiency, reducing the operational duration of instruments and equipment, and promoting energy conservation and emissions reduction.

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