The Indoor Air Quality, Ventilation and Energy Nexus in the COVID-19 Context

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Abstract. In the face of the Covid-19 pandemic and environmental crises, ventilation plays a critical role in the removal of infectious pathogens. A building ventilation paradigm results in excessive energy consumption to ensure indoor air quality. At the time of writing this paper, several studies have been conducted regarding COVID-19 and ventilation; however, the energy challenges of ventilation operation under the pandemic condition has not been fully addressed by previous studies. This paper is based on a literature review of publications, using an internet-based search in different scientific databases. A data-driven keyword analysis on bibliographic data was performed based on English-language textual data of more than 267 publications downloaded from Dimensions website and using VOSviewer, a freely available software tool for analysing bibliographic data. Via analysis of co-occurrence of the specific terms in the field of COVID-19 ventilation, the trends in research publications were illustrated. The study aims to review the scientific literature of the indoor spread of SARS-CoV-2; clarify the effect of ventilation systems on airborne transmission of the virus; identify the impacts of COVID-19 mitigation measures on the energy consumption of mechanical ventilation systems; define the research gaps and future challenges. This investigation reveals a strong need for more scientific studies in reduction of the transmission risks of the SARS-CoV-2 virus through ventilation systems without compromising buildings' energy performance. The implications of this study will establish a foundation for engineering control strategies and future energy-targeted investigations for virus transmission reduction and the enhancement of indoor air quality.

Keywords. COVID-19, indoor air quality, mechanical ventilation system, building energy performance, healthy indoor environments.
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1. Introduction

The COVID-19 pandemic has exposed areas requiring urgent development to provide a healthy indoor environment [1]. Given that most of the documented spread of the disease has happened in indoor environments [2], control of indoor air is essential to reduce the risk of airborne pathogens [3]. Engineering controls through heating, ventilation, and air-conditioning (HVAC) systems are considered a higher level of precaution than physical containment methods for creating healthy indoor environments [4; 5; 6; 7; 8]. Ventilation is the primary control measure for indoor transmission of airborne particles [1]. Existing ventilation systems in buildings are designed to remove heat and pollution loads in normal conditions. However, ventilation systems should also be able to eradicate the transmission of airborne particles during serious outbreaks [9]. In addition, an inadequate ventilation rate and inappropriate ventilation strategy are associated with inferior health outcomes for the occupants.

Energy consumption linked with control of the indoor environment is a critical concern, given that buildings consume over 36% of energy globally [10]. New ventilation criteria, proposed by industry professionals, have mainly focused on indoor air quality improvements to guarantee occupants' health. However, the associated energy consumption was an afterthought; this has resulted in high energy consumption as a result of increased volumes of fresh air being treated and delivered during the pandemic [11]. Higher ventilation rates required to flush air out of a space in a short period exceed the capacity of most of the existing mechanical ventilation systems and might result in discomfort to occupants as well as non-optimal performance from a cost perspective. In regard to this matter, Lipinski et al. (2020) assessed the current ventilation strategies intending to decrease the risk of pathogen transmission and to adapt ventilation measures to new threats posed by pandemics [3]. Melikov (2020) proposed a paradigm shift in the design of future ventilation with a specific focus on the occupant but not space [12]. Thus, the challenge is how to balance the ventilation energy use and the prevention of infection risk in the indoor environment and to recommend strategies that help to deliver a healthy yet sustainable indoor environment [8].

Although many papers have been published regarding indoor air quality, ventilation and COVID-19 spread, very few of them have mentioned the energy challenges of ventilation operation due to these requirements. Aiming to identify the impacts of COVID-19 on the energy consumption of mechanical ventilation systems, this paper reviews the research, conducted on:

1. the couplings of reducing infection risks of SARS-CoV-2, operating ventilation systems and reducing energy consumption;

2. the scientific literature of the indoor spread of SARS-CoV-2 and the transmission routes are also reviewed and the effect of ventilation systems on airborne transmission of the virus is then clarified;

3. the gaps of adaptation on the three aforementioned areas (Figure 1).

Aiming to demonstrate the evolution of the scientific landscape of COVID-19 ventilation and energy efficiency through bibliometric analysis, the implications of this research lead to a new discussion of the assessment of operating ventilation systems in relation to the connected energy consumption and healthy indoor environment. This could be essential for proposing effective and energy-efficient solutions for adapting ventilation systems to the pandemic context.

1.1 The indoor spread of SARS-CoV-2 and transmission

To understand the role of ventilation systems in keeping indoor environments virus-free and reducing energy consumption, it is important to know the characteristics of SARS-CoV-2 and its trajectories. This section elaborates the indoor spread of this virus and its transmission routes.

SARS-CoV-2 belongs to the betaCoVs category. Considering that the virus has a diameter of approximately 60–140 nm [13], it can be easily transmitted by aerosol droplets in the air and stay float for a period depending on factors like heat and humidity [3; 14]. Many studies suggested SARS-CoV-2 may be airborne and is stable on aerosols for 3 hours, and can travel a long distance in the closed and open environments [9; 12; 14; 15; 16] via three main routes, including droplet, contact, and airborne routes. The airborne route (also called aerosol transmission) happens when exhaled respiratory droplets are small enough to remain suspended that they can be inhaled into the respiratory system of other people [1; 3; 17; 18; 19].

The distance particles move away from the infected person depend on several factors, including the size of the particles, initial momentum they are expelled (i.e., type of respiratory activity), the position of the head and the body of the person generating the particles, strength (velocity), structure (turbulent or laminar), direction, temperature and humidity of the surrounding air flow, individual differences between people regarding respiratory activities, etc. [3; 20; 21; 22; 23; 24; 25]. Li et al. (2021) measured the main influencing factors of the exposure risk of SARS-CoV-2, namely the occupant density, dwell time, and fresh air volume per person, in retail buildings [26].

Also, successful infection depends on exposure (inhaled dose of particles with viruses) and time. With regard to the distance between infected and exposed persons, short-range exposure to large and small particles and long-range exposure mainly to small airborne particles can be defined. The risk for short-range exposure is much higher than long-range exposure. Research shows that a rise in outdoor air supply to occupied spaces can reduce the risk of long-range exposure but is less effective in reducing the short-range exposure [12].

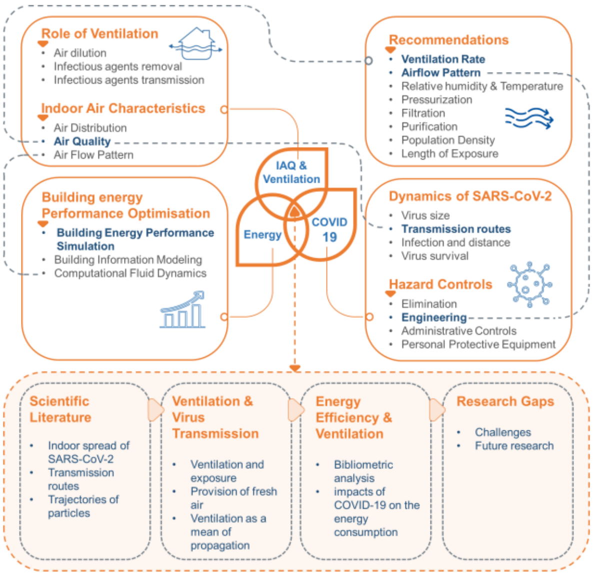

Fig. 1 – Structure of the research.

1.2 Effect of Ventilation Systems on Airborne Transmission of the Virus

Ventilation can be defined as "the process of introducing and distributing outdoor and/or properly treated recycled air into a building or a room" [27] or "the process by which "clean" air (normally outdoor air) is intentionally provided to space and stale air is removed" [28]. Due to the short-fall in the stable wind pressure, natural ventilation systems are usually used for auxiliary purposes and mechanical ventilation systems are largely utilized to meet requirements for indoor air quality [8]. In the recent research, Nembhard et al. (2020) reviewed the role of building ventilation in minimizing the risk of SARS-CoV-2 transmission in non-medical settings [6]. Also, Blocken et al. (2021) measured the aerosol particle removal by mechanical ventilation and mobile air cleaning units in a gym. They concluded that the combination of existing ventilation supplemented with air cleaning is energy efficient and can also be applied to other indoor environments [29].

The principle of ventilation to control the airborne transmission of viruses mainly includes two aspects, namely, diluting viral concentration and blocking virus transmission [9; 30]. The dilution is managed either by supplying outdoor air mixing with the existing indoor air; or by attempting to enter the outdoor air into the occupied zone of the building space in a relatively unmixed state and then "displace" any air polluted by airborne virus particles back outdoors [31; 32]. The Air Changes per Hour (ACH) is a measurement of how much fresh/clean air replaces indoor air in 1 hour [33], which is more widely adopted in engineering to determine if ventilation and air conditioning systems can provide adequate ventilation rate to guarantee a low infection probability [34]. The recently updated guidelines for the reduction of airborne infection recommend a substantial increase in the ventilation rate [35; 36]. In this matter, Dai & Zhao (2020) estimated the link between the infection probability and ventilation rates with the Wells–Riley equation for some typical scenarios, including offices, classrooms, buses, and aircraft cabins [34]. Pease et al. (2021) evaluated the concentrations and probabilities of infection and concluded that increasing the fraction of virus-free outdoor air is helpful unless outdoor air is infective [37].

2. Research Methods

2.1 Bibliometric analysis

The bibliographic data was collected from 267 publications published from December 2019 to July 2021 from the Dimensions bibliographic database [38]. It must be noted that several search query words with "AND" as a Boolean operator were used to create a total of 5 combinations of specific query wording of "SARS-CoV-2" AND "ventilation" AND "COVID-19" AND "indoor air quality" AND "energy." Data-driven keyword analysis on bibliographic data was performed using VOSviewer, a freely available software tool for analysing bibliographic data [39].

Through analysis of co-occurrence of field-specific terms, this software visualises the trends in research publications. Out of a total of 7418 terms identified occurring in the titles and abstracts, the terms with a minimum of five occurrences and the top 15 according to relevance were extracted from English-language textual data, unrelated words were eliminated, and abbreviations were replaced by full terms. It is important to mention that although the bibliographic tools greatly reduce the time spent analysing bibliographical sources, human supervision on the results is still needed. In this paper, we analysed and elaborated the results obtained from the software analysis. This produced a network visualisation of terms, where each circle represents a term and the label and circle size of a term determines its importance (the higher the importance, the larger the label and circle); the link corresponds to a connection between two terms, and its strength represents the strength of co-occurrence; The distance between two terms is

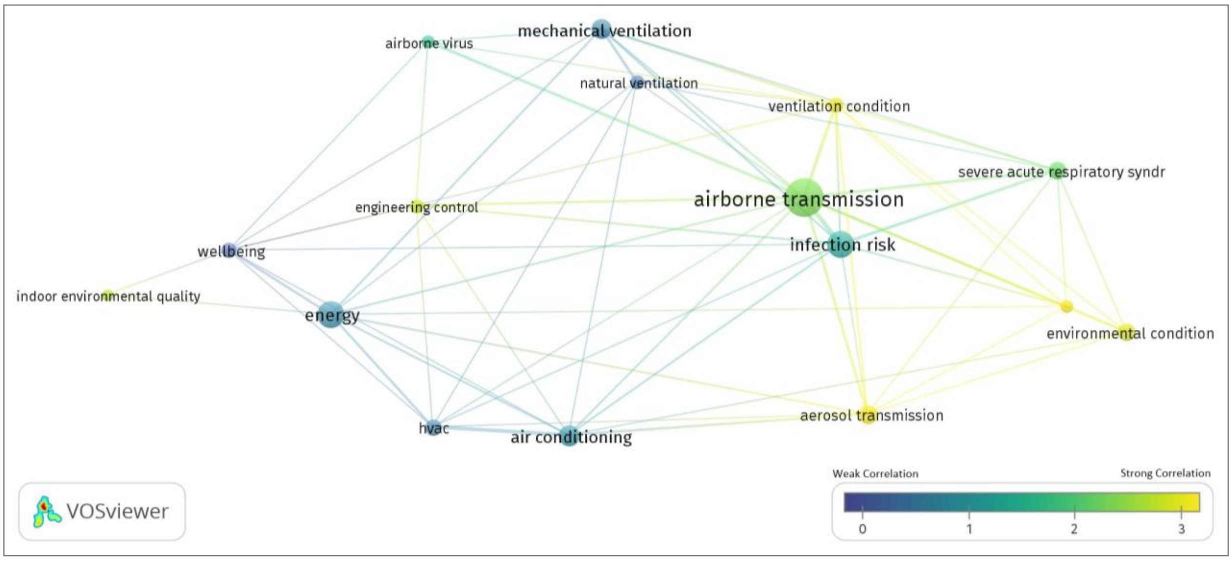

Fig. 2 - Keyword network visualization of terms.

representative of their relatedness; terms that co-occur a lot tend to be located close to each other in the visualization. Finally, the network was colour-overlaid where the colour assigned shows the strength of co-occurrence, enabling the analysis of the importance of the term in the literature (Figure 2). Analysing Figure 2, it could be determined that:

- The core topic in the literature with the highest link strength is the airborne transmission SARS-CoV-2.
- There is a strong link between the terms aerosol transmission, ventilation, and environmental condition with the assigned yellow colour, indicating a rise in awareness of the importance of these couplings.
- Decreasing the occurrence of the terms energy, mechanical ventilation, air conditioning, and well-being demonstrates insufficient studies and research on the topics on which this paper is focusing.
- There is a multi-faceted and multi-dimensional character of this particular scientific field.

3. The impact of COVID-19 on the energy consumption of mechanical ventilation systems

Although measures provided by various industry associations and HVAC operators have the potential to reduce infection risks, they need extra energy use by the HVAC system, which might simply be wasting energy without providing a meaningful reduction in transmission risk [4; 9].

Higher ventilation means higher energy use [30]; ventilation should be adequate to the demand but not unnecessarily high [30; 40; 41]. If future ventilation systems are designed to supply a large amount of outdoor air during the pandemic, they will not operate economically under normal conditions (no pandemic) with a greatly reduced supply airflow rate [12]. On this matter most of the papers have focused on high-density indoor environments. More specifically, the following three papers have targeted the building occupants as the transmission source of infection diseases by applying the occupant-related information, in particular, occupant presence schedule. Wang et al. (2021) proposed an intelligent, low-cost ventilation control strategy based on an occupant-density-detection algorithm that can actively self-adjust the ventilation rate when experiencing different occupant densities considering both infection prevention and energy efficiency. Melikov et al. (2020) proposed an improved control strategy based on source control, which would be achieved by implementing intermittent breaks in a typical classroom [42]. Through a multi-objective optimization, Mokhtari & Jahangir (2021) examined the optimum occupant distribution models that account for the lowest number of infected people and minimum energy use in a university building [43].

Concerning other high-density environments, a large number of studies have focused on educational buildings, in particular, school and university classrooms using experimental and numerical investigations [42; 43; 44; 45; 46]. In their findings, Balocco & Leoncini (2020) showed that it is possible to obtain healthy school environments by means of an optimal compromise between energy savings and proper management of mechanical ventilation systems for indoor air quality [44].

Ascione et al. (2021) proposed a comprehensive approach for the retrofit design of university classrooms through both experimental studies and by the coupling of different numerical methods of investigations and building performance simulations [45]. Aviv et al. (2021) analysed the energy consequences of increasing the fresh air delivered through typical commercial building recirculating ventilation systems. Their results suggested the coupling of natural ventilation and radiant systems [47]. On the matter of energy efficiency of ventilation systems in school classrooms, Schibuola & Tambani (2021) investigated the possibility of containing COVID-19 contagion in indoor environments via increased ventilation rates obtained through high energy efficiency systems combining thermal recovery by a heat exchanger and thermodynamic recovery by a heat pump [46]. The controlled parameters studied in these papers have been mostly and commonly based on the indoor distribution of microclimatic parameters (i.e., air temperature, air velocity and flow fields, indoor thermal comfort, age of air) [44; 45; 47; 48] indoor/outdoor CO2 concentrations [46] and their effects on the indoor infection probability and energy consumption [4; 11; 49]. The effects of these parameters were mainly studied in indoor environments with high occupancy, where infection probability is high [42; 43; 44; 45; 46; 47; 49]. However, in terms of the building type, there is a gap to study the energy performance of the ventilation system and indoor air quality in low-occupancy buildings such as homes and small offices. Table 1 summarises the reviewed papers in this field. Reviewing the abovementioned papers and analysing Table 1, it could be determined that:

- As most of the papers have focused on high-density indoor environments such as educational buildings where infection probability is high, there is small diversity of case studies in the published literature and very few preliminary studies in low-occupancy indoor environments.
- Several studies have highlighted improved ventilation control strategies based on source control and the optimum occupant distribution.
- There has been considerable interest in studying the indoor distribution of

microclimatic parameters, pollutant concentration and infection probability in the literature.

4. Discussion

Through the above review and discussions, the research gaps of adaptation on the three aforementioned areas were highlighted in this section. According to these gaps, attention should be paid to adapting ventilation designs to the normal and pandemic situations simultaneously and to operating HVAC systems in a relatively low energy consumption mode during the pandemic period. HVAC system auxiliary equipment should also be developed for energy savings and improving indoor air quality. Optimization of ventilation systems, indoor air quality, and energy efficiency is another significant gap in this nexus. Additional studies are also required on the energy efficiency assessment of novel mechanical ventilation methods and control strategies that can significantly improve effective ventilation performance in different building types with varying occupancy densities. Figure 3 represents the gaps found in the literature.

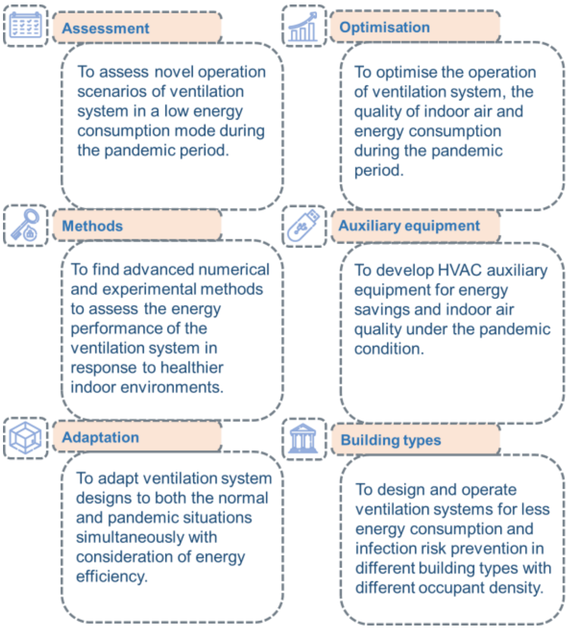

Fig. 3 - Research gaps in the literature.

5. Conclusion

The pandemic mitigation set of measures forces the adaptation of existing buildings and changes to new paradigms, where health is preferred over energy efficiency. The current approach would result in higher energy consumption, in buildings in a post-COVID-19 period. It is crucial to identify the most influential research channels and major concerns of the design and operation of effective ventilation systems and energy consumption to meet future challenges. This article presented an up-to-date bibliometric analysis to describe and assess the scientific landscape of COVID-19 ventilation and energy consumption. The results of bibliometric analysis demonstrates insufficient studies and research on the topics on which this paper is focusing.

Through reviewing the most cited publications in this literature, and analysing the main theme, method, results, parameters and the building type investigated in these papers, the research gaps and future challenges are highlighted and summarised in six main categories including the assessment and optimisation of ventilation operation during the pandemic period; the advanced numerical and experimental methods of assessing the energy performance of the ventilation system; the development of HVAC auxiliary equipment for better energy savings and indoor air quality; the adaptation of ventilation system design to both normal and pandemic situations; and to consider these items in diverse building types with different building densities.

Given the struggle between energy sustainability and occupant wellness, it is essential to make indoor air quality a priority parameter in the design of a building. If the design and operation of the mechanical ventilation systems are oriented towards the health of the users, the virus transmission can be significantly reduced. Thus, greater integration is needed to ensure that energy efficiency interventions are carried out simultaneously, with indoor air quality provision. This is very much the key component in future attempts to overcome the conflicts between energy efficiency and indoor air quality.

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Data access statement: The datasets generated and analysed during the current study are not publicly available in the Dimensions Website because the access requires login credentials; but the data will be available by creating an account and inserting search string terms as discussed in the Research Methods section.

Tab. 1 - Overview of research in energy efficiency of ventilation systems in the context of COVID-19.

Reference	Methodology	Results	Building Type	Main Theme	Studied Parameter
[4]	• Modelling the transmission rate by considering the airborne concentration of infectious particles. • Estimating the energy consumption by considering the change in HVAC variables and applying standard models.	• Underlying transmission risk and the energy-optimal disinfection strategies can vary significantly from building to building and from space to space.	• Not specified	• Infection rate • Energy consumption	• Concentration of infectious particles, activity, dimensions of the space, HVAC operation • Flow rates and temperatures
[11]	• Comparing energy consumption, CO2 emissions and operations costs in nine US climate zones between the previous and post COVID-19 scenarios using BES.	• Climate zones above mixed-humid type tend to increase relative energy use intensity by 21.72%, but below that threshold the zones decrease relative energy use intensity by 11.92%.	• High-rise office buildings	• Energy consumption • CO2 emissions • Operation costs	• Cooling & heating • Lighting • Fans &Plug & equipment, pumps, SWH • CO2 emissions
[41]	• Different factors and strategies are reviewed and discussed. • Suggested mitigations and solutions are provided.	• Need for in situ experimental studies to understand the different scenarios of the virus spread. • The human factor should also be considered.	• Not specified	• Technological solutions for HVAC systems	• Underfloor air distribution • Chilled beams & Radiant ceiling panels, Laminar flow systems • HEPA filter & UV light
[42]	• Aerosols concentration prediction. • Evaluation of the risk of airborne cross-infection calculating the time-averaged intake fraction.	• An improved control strategy based on source control, can be achieved by implementing intermittent breaks in room occupancy.	• Classroom	• Occupant presence schedule • risk of air-borne cross-infection	• Supply flow rate • Schedule of lessons and breaks • Density, Room height • Number of source
[43]	• A multi-objective optimization used with the objectives of energy consumption and COVID-19 infected people, using NSGA-II algorithm.	• An optimal population distribution can reduce the number of infected people and energy consumption.	• University building	• Energy consumption • COVID-19 infection	• Occupant presence schedule • ACH • Class duration • Working hours
[44]	• Transient simulations.	• Correct behaviour, together with proper management and maintenance of a mechanical ventilation guarantee indoor air quality and healthy environments.	• Schools	• Demand-controlled mechanical ventilation	• Indoor Air Temperature • Air Change per Hour (ACH) • Energy Cost
[45]	• A numerical model of a University building was proposed and the design of refurbishment was performed by coupled numerical methods, Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD).	• New scenarios and evidenced the usefulness of HVAC systems, equipment and suitability of some strategies for the air distribution systems compared to traditional ones.	• University classrooms	• Energy impacts • Indoor distribution of microclimatic parameters	• Annual & monthly primary energy demand • Indoor distribution of microclimatic parameters & thermal comfort • Age of air
[46]	• Evaluation of the infectious risk by using measurements of indoor/outdoor CO2 concentrations to calculate actual ACH.	• There is possibility to achieve a reduction in energy consumption as a result of installing an autonomous high efficiency air handling unit (HEAHU).	• Schools classroom	• Energy consumption	• ACH • Indoor/outdoor CO2 concentrations
[47]	• Analysing the energy consequences of increasing the fresh air and the potential of alternative radiant and convective systems to compensate using thermal comfort models combined with global weather data.	• It is possible to add up to 100 days' worth of natural ventilation while saving energy, when coupling natural ventilation and radiant systems.	• Typical commercial building	• HVAC energy cost	• The increasing outdoor air ratio • Thermal comfort indoors
[48]	• Optimization of the in-duct Ultra Violate Germicidal Irradiation (UVGI) system using CFD simulation and energy simulation.	• Identifying two energy-efficient UVGI system designs as references during the COVID-19 pandemic.	• Not specified	• Germicidal source output • UV rate constant • System inactivation efficiency • System energy consumption	• Air temperature • Air velocity • Relative humidity
[49]	• YOLO (You Only Look Once) algorithm was applied for occupancy detection.	• Infection probability reduction and energy saving increase.	• Public transportation buildings	• Occupant density	• Infection probability • Energy consumption
[50]	• Editorial Review	• Risk reduction of exposure and virus contamination through focusing on the health of the users	• Not specified	• Energy efficiency • Indoor air quality	• Not specified

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