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Prevention and Control of Nosocomial Pneumonia

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TABLE OF CONTENT

Abstract	3
1. INTRODUCTION	5
1.1 Background and Importance of Nosocomial Pneumonia in ICUs	5
1.2 Epidemiology and Disease Burden	5
1.3 Relevance and Novelty of the Topic	7
1.4 Aim and Objectives of the Thesis	7
2. METHODOLOGY	8
2.1 Type of Study: Extended Literature Review	8
2.2 Purpose of the Literature Review	9
2.3 Search Databases and Keywords Used	9
2.4 Inclusion and Exclusion Criteria	11
2.5 Limitations of the Literature Search	12
3. LITERATURE REVIEW	13
3.1 Definition and Classification of Nosocomial Pneumonia	13
3.2 Pathophysiology and Microbiological Aspects	13
3.3 Risk Factors Among ICU Patients	15
3.4 Preventive Strategies	16
3.5 Emerging technologies and future prevention trends	29
4. DISCUSSION	35
4.1 Synthesis of Key Findings	35
4.2 Comparison with International Guidelines (CDC, WHO, ECDC)	37
4.3 Gaps in Current Evidence	38
4.4 Implications for ICU Practice and Policy	39
5. CONCLUSIONS AND RECOMMENDATION	40
5.1 Summary of Main Conclusions	40

5.2 Recommendations for Clinical Practice.....	42
REFERENCES	44
ARTIFICIAL INTELLIGENCE DISCLOSURE	49

*Table 1: List of
Abbreviation*

Abbreviation	Full Term
AMS	Antimicrobial Stewardship
ARDS	Acute Respiratory Distress Syndrome
CDC	Centers for Disease Control and Prevention
CHX	Chlorhexidine
CINAHL	Cumulative Index to Nursing and Allied Health Literature
COVID-19	Coronavirus Disease 2019
CRAB	Carbapenem-Resistant <i>Acinetobacter baumannii</i>
DVT	Deep Vein Thrombosis
ECDC	European Centre for Disease Prevention and Control
ETT	Endotracheal Tube
GCS	Glasgow Coma Scale
HAP	Hospital-Acquired Pneumonia
HOB	Head-of-Bed
ICU	Intensive Care Unit
ICUs	Intensive Care Units
IVAC	Infection-Related Ventilator-Associated Complication
LMICs	Low- and Middle-Income Countries
MDR	Multidrug-Resistant
MDROs	Multidrug-Resistant Organisms
MeSH	Medical Subject Headings
MRSA	Methicillin-Resistant <i>Staphylococcus aureus</i>
NP	Nosocomial Pneumonia
NHSN	National Healthcare Safety Network
NV-HAP	Non-Ventilator Hospital-Acquired Pneumonia
PICO	Population, Intervention, Comparison, Outcome
	Peptic Ulcer Disease

PUD	Possible Ventilator-Associated Pneumonia
PVAP	
RCTs	Randomized Controlled Trials
RSV	Respiratory Syncytial Virus
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SBT	Spontaneous Breathing Trial
SDD	Selective Digestive Decontamination
SHEA/IDSA	Society for Healthcare Epidemiology of America / Infectious Diseases Society of America
SSD	Subglottic Secretion Drainage
VAC	Ventilator-Associated Condition
VAE	Ventilator-Associated Event
VAP	Ventilator-Associated Pneumonia
VUSIS	Vilnius University Study Information System
WHO	World Health Organization

Abstract

Nosocomial pneumonia, and especially Ventilator-Associated Pneumonia is one of the major issues in the Intensive Care Unit of different countries, entailing significant patient morbidity, mortality, and health expenditures. This is an integrated study master thesis in the form of a lengthy literature review, wherein the available evidence (2020-2025) on the best approaches toward the prevention and control of Nosocomial pneumonia in the Intensive Care Unit is critically evaluated. That is the research proves that Ventilator-Associated Pneumonia rates are disproportionately elevated in low- and middle-income countries and that the Coronavirus Disease 2019 pandemic made the quest to combat infections more complicated. The essence of any successful prevention is a systematic use of evidence-based care bundles, which are merely bundles of practice, which, when applied together, considerably decrease the rate of Ventilator-Associated Pneumonia. The main elements of such bundles are daily readiness assessment to extubate, reducing the length of mechanical ventilation, head of the bed lift to 30 -45 degree, ensuring endotracheal tube cuff pressure, and oral care with a toothbrush. Beyond clinical aspect, the review also emphasizes the importance of a multidimensional approach, which combines education, surveillance, compliance monitoring, internal reporting, and performance feedback. In addition, organizational aspects like well staffed Infection Prevention Program, efficient laboratory backup, and the utilization of

epidemiological information to inform empirical antibiotic therapy are necessary to achieve long term success. The thesis sums up that despite the major developments in that field, especially with Ventilator-Associated Pneumonia, non-ventilator hospital-acquired pneumonia is the field that needs more research and specific preventative measures. The recommendations are aimed at reinforcing the adherence to the predetermined bundles, developing the staff education, and using technology to provide real-time surveillance and feedback in order to eventually improve patient outcomes in the Intensive Care Unit.

Santrauka

Nosokominė pneumonija, ypač su dirbtine plaučių ventiliacija susijusi pneumonija (VAP), yra viena iš pagrindinių problemų įvairių šalių intensyviosios terapijos skyriuose, lemianti reikšmingą pacientų sergamumą, mirtingumą ir sveikatos priežiūros išlaidas. Šis integruotas magistro darbas yra išsamios literatūros apžvalgos forma, kurioje kritiškai vertinami 2020–2025 m. prieinami įrodymai apie geriausius nosokominės pneumonijos prevencijos ir kontrolės būdus intensyviosios terapijos skyriuose. Tyrimas rodo, kad su dirbtine plaučių ventiliacija susijusios pneumonijos dažnis yra neproporcingai didesnis mažas ir vidutinės pajamas gaunančiose šalyse, o COVID-19 pandemija dar labiau apsunkino infekcijų kontrolę

Sėkmingos prevencijos pagrindas yra sistemingas įrodymais pagrįstų priežiūros paketų taikymas – tai praktikų rinkiniai, kurie, taikomi kartu, reikšmingai sumažina VAP dažnį. Pagrindiniai šių paketų elementai yra kasdienis pasirengimo ekstubacijai vertinimas, mechaninės ventiliacijos trukmės mažinimas, galvos pakėlimas 30–45° kampu, tinkamo endotrachėjinio vamzdelio manžetės slėgio užtikrinimas bei burnos priežiūra naudojant dantų šepetėlį.

Be klinikinių aspektų, apžvalgoje pabrėžiama daugiamatės strategijos svarba, apjungianti mokymą, stebėseną, atitikties kontrolę, vidinę atskaitomybę ir grįžtamąjį ryšį apie veiklos rezultatus. Taip pat akcentuojami organizaciniai veiksniai, tokie kaip tinkamai sukomplektuota infekcijų prevencijos programa, efektyvus laboratorinis palaikymas ir epidemiologinių duomenų naudojimas empirinei antibiotikų terapijai parinkti – visa tai būtina ilgalaikiai sėkmei užtikrinti.

Darbo išvadose teigiama, kad, nepaisant reikšmingos pažangos šioje srityje, ypač VAP atveju, ne su ventiliacija susijusi ligoninėse įgyta pneumonija išlieka sritis, kuriai reikia daugiau tyrimų ir specifinių prevencijos priemonių. Pateiktos rekomendacijos skirtos stiprinti nustatytų priežiūros paketų laikymąsi, plėtoti personalo mokymą ir diegti technologijas,

leidžiančias vykdyti realaus laiko stebėseną bei grįžtamąjį ryšį, siekiant gerinti pacientų gydymo rezultatus intensyviosios terapijos skyriuose.

Keywords

Nosocomial Pneumonia, Ventilator-Associated Pneumonia, Intensive care unit, Infection control, Care bundle, Prevention strategies, antimicrobial stewardship, Critical care.

1. INTRODUCTION

1.1 Background and Importance of Nosocomial Pneumonia in ICUs

Nosocomial pneumonia or Hospital-acquired pneumonia (HAP) refers to the pneumonia that occurs in a patient within 48 hours or later after being admitted in a hospital as long as it was not present before admission. Ventilator associated pneumonia (VAP), a subset of HAP, occurs in intensive care units (ICUs) in patients receiving mechanical ventilation, typically more than 48-72 hours post-intubation. VAP occurs in about 10-20 percent of patients who are under mechanical ventilation more than 48 hours [1].

1.2 Epidemiology and Disease Burden

Incidence and Variability

Ventilator-associated pneumonia (VAP) is a common complication in the management of patients in intensive care units (ICUs), especially those patients who are undergoing invasive ventilation [2]. Although the incidence of VAP is reported to differ, one of the studies suggested that it happens in about 30 percent of patients put on ventilators in ICUs, and the incidence varies with different factors, including the particular environment and demographics of the patient [3]. In other center studies, the incidence densities of VAP are between about 20 and 30 episodes per 1,000 ventilator-days (e.g., 20.1 per 1,000, bronchoalveolar lavage diagnosis) and can be higher [4].

The rate of ventilator-associated pneumonia (VAP) has been typically high in low- and middle income countries (LMICs) and amid the COVID-19 pandemic [5]. Such differences probably have to do with differences in definitions of surveillance, testing methods, type of patients (e.g. a higher presence of immunocompromised or post-surgical patients), and the resources available to prevent infections [5]. Moreover, non-ventilator hospitals acquired pneumonia

(NV-HAP) and ventilator-associated events (VAE) still play a significant role in the burden of infections in intensive care units (ICUs) [6].

Outcomes

Research indicates that non-ventilator hospital-acquired pneumonia (NV-HAP) and ventilator associated pneumonia (VAP) is linked with poor outcomes, including longer inpatient mortality, increased discharge to hospice or long-term care units, and high healthcare resource utilization, such as long ICU and hospital stays, and high healthcare costs [7]. One of the most notable multicenter studies on VAP recorded a mortality rate of 59 percent within the 30 days stay of a varied ICU patient population [4]. Systematic review reveals that it is not easy to clearly estimate the mortality rate that ventilator-associated pneumonia (VAP) directly causes because of the inconsistent estimates. Nonetheless, its persistent correlation with long-term intensive care unit (ICU) stays, long-term mechanical ventilation, and augmented organ dysfunction underscores the high level of patient morbidity caused by the VAP.

Ventilator-associated pneumonia (VAP) is attributable to significant increment of extraneous costs, as one narrative review reported an escalation of \$40,144 in the United States per case [2].

Microbiology and Resistance

Gram-negative bacilli such as *pseudomonas aeruginosa*, *Enterobacter ales*, and *Acinetobacter spp.*, and *staphylococcus aureus* are common causes of nosocomial pneumonia in the ICUs [2]. The increase in prevalence of multi-drug-resistant organisms (MDROs) makes them hard to treat and results in a worse outcome [9]. Recent systematic review and meta-analysis reported a combined prevalence of multi drug-resistant *P. aeruginosa* in ventilator-associated pneumonia (VAP) of approximately 33.0, (95%CI 27.7-38.3%), even though there was great disparity in the prevalence across countries, with a high prevalence of 87.5% in Iran and low prevalence of 19.7% in the USA [9]

Resource-Level and Pandemic Considerations

There are major discrepancies between regions and resource environments where low- and middle-income countries (LMICs) show greater incidence rates and poor outcomes in many observational studies [5]. These disparities are mainly explained by the staffing shortages, equipment (e.g., accessibility to subglottic drainage tubes or cuff-pressure monitors),

infection control facilities, and diagnostic abilities [5]. The COVID-19 pandemic changed the situation with the VAP:

1. VAP rates significantly increased among ICU patients with severe SARS-CoV-2 infection [6].
2. Pathogen profiles shifted to certain ICU populations [10].
3. The overwhelming number of critically ill patients strained infection prevention resources [6], collectively exacerbating the clinical and systemic impact of nosocomial pneumonia during and following pandemic surges.

1.3 Relevance and Novelty of the Topic

Nosocomial Pneumonia prevention and control in ICU is an important measure to increase patient safety and antimicrobial stewardship [11]. Evidence-based interventions, such as bundles of care, oral hygiene, and draining of the subglottic secretion, can greatly decrease the use of antibiotics and the prevalence of multi drug resistant organisms [12]. Recent research has helped to polish our thinking on which elements in bundles work, as well as showing gaps in knowledge, including the efficacy of chlorhexidine oral care and optimal methods of subglottic suctioning [13,14]. A contemporary analysis of such innovations is crucial to the direction of ICU practices and policies.

1.4 Aim and Objectives of the Thesis

Although preventive strategies are continued to be employed, nosocomial pneumonia, especially ventilator-associated pneumonia (VAP), is one of the critical care issues [8]. Recent evidence (2020-2025) suggests that ventilator care bundle have led to a reduction in the incidence of VAP rate in some high-income regions, but that the incidence of VAP is still high in many ICUs [15], particularly in resource-limited units and in patients with severe respiratory disease, such as COVID-19-related ARDS [6].

Subglottic secretion drainage and oral care strategies are effective in preventing infections, but not all of them are equally effective based on their implementation and the culture of the ICUs [13,14]. The differences in study design and diagnostic criteria do not allow comparisons and translation into clinical practice [16]. The problem of antimicrobial resistance of VAP pathogens is rising, which underscores the necessity of preventing and controlling the infection [9].

The purpose of this review is to critically evaluate existing evidence on the topic of preventing and controlling nosocomial pneumonia among patients in the ICU including the effective

interventions, implementation strategies, and novel innovations to minimize morbidity, mortality, and healthcare burden. Key areas include:

- The epidemiology and burden of nosocomial pneumonia in the ICU.
- Preventive strategy effectiveness.
- Influence of local setting and quality of implementation.
- Existing gaps and possible future research needs in the field of the prevention and control of VAP.

Specific Objectives

1. Scale up existing epidemiological, disease burden and microbiological trends of nosocomial pneumonia in ICUs using the international and regional data (2020-2025).
2. Describe patient, equipment, and environmental risk factors that lead to nosocomial pneumonia that causes ICUs.
3. Take into account the effectiveness of preventive measures, including ventilator care bundles, subglottic secretions drainage and oral care.
4. Determine how antimicrobial stewardship programs can help decrease antimicrobial resistance and enhance patient outcomes.
5. Look into organizational and educational interventions to improve adherence to infection prevention measures.
6. Discover new technologies and innovations in preventing nosocomial pneumonia, including new airway machine devices and automated monitoring systems.
7. Identify the gaps and limitations in the current literature and practice and provide evidence based suggestions to improve the existing policies on infection-prevention in the ICU and future studies.

2. METHODOLOGY

2.1 Type of Study: Extended Literature Review

This study is in the form of a long literature review of the prevention of nosocomial pneumonia particularly ventilator-associated pneumonia (VAP) among adult patients in the intensive care unit (ICU) [1,2]. It includes randomized controlled trials (RCTs), systematic reviews, meta analyses, cohort studies, and international clinical guidelines that are published since January 2020 and are included in the synthesis and critical evaluation. Unlike a systematic review that has a rigid PRISMA template, this literature review has incorporated quantitative and

qualitative data to discuss the usefulness of the interventions, contextual and implementation factors that affect the success of delivery of the interventions. This methodology is consistent with the recent guidelines of infection prevention, as it focuses on implementation science views and use of evidence contextualization in the critical care [7,15].

2.2 Purpose of the Literature Review

The current evidence (2020-2025) on preventive and controlling measures of nosocomial pneumonia in Intensive Care Unit (ICU) patients, and more so ventilator-associated pneumonia (VAP) is critically analyzed and synthesized in this literature review [3,6]. It will determine and assess evidence-based interventions that are effective in the prevention of the occurrence, morbidity, and mortality of nosocomial pneumonia in critical-care units [12,15].

Considering the complexity of ICU settings and multifactorial aspects of infection risk, this review combines the results of epidemiological studies, clinical trials, systematic reviews, and implementation research to gain a clear understanding of preventive strategies [6,17,18].

It also investigates the effects of contextual as well as organizational factors that play a role in determining the success or failure of infection-control interventions [5].

The first one is to produce evidence-based recommendations that enhance clinical practice, enhance policy development, and inform future research on the prevention of nosocomial pneumonia in critical-care units [12,15].

2.3 Search Databases and Keywords Used

An effective literature search was carried out in order to find out the good evidence available about prevention and control of nosocomial pneumonia especially ventilator-associated pneumonia (VAP) in adult patients at intensive care unit (ICU) [1,2].

The search was to identify new studies that were published in the year 2020 to October 2025 to ensure that the current studies, guidelines and implementation research that are related to ICU infection prevention are identified [6,7,15].

Table 2: Databases Searched

Database	Primary Focus
PubMed/MEDLINE	Peer-reviewed biomedical and clinical studies.
Cochrane Library	Systematic reviews, meta-analyses, and evidence-based guidelines.

Scopus and Web of Science	Multidisciplinary research, citation tracking, and comprehensive literature coverage.
ScienceDirect (Elsevier)	Full-text access to clinical, microbiology, and critical care journals.
CINAHL	Nursing and allied health literature relevant to ICU care.
Google Scholar	Supplementary grey literature, preprints, conference proceedings, and other nonindexed publications.

All searches were limited to English-language publications and were conducted in October 2025.

Search Strategy

The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to nosocomial pneumonia, ICU care, and prevention, using Boolean operators “AND” and “OR” to refine results. The search was guided by the PICO framework. *Table 3: PICO Framework*

PICO Element	Description
Population	Adult ICU patients
Intervention	Preventive strategies for nosocomial or ventilator-associated pneumonia
Comparison	Standard care or alternative preventive interventions
Outcome	Reduction in incidence, morbidity, or mortality due to nosocomial pneumonia

Sample Keywords and Concepts

Table 4: Keywords and Concepts

Concept	Keywords
Nosocomial Pneumonia	“nosocomial pneumonia”, “hospital-acquired pneumonia”, “HAP”, “ventilator associated pneumonia”, “VAP”
Population	“intensive care unit”, “ICU”, “critical care”, “critically ill patients”, “mechanically ventilated patients”
Prevention	“infection control”, “preventive strategies”, “VAP bundles”, “oral care”, “subglottic drainage”, “patient positioning”, “sedation management”,

	“antimicrobial stewardship”, “staff training”, “implementation fidelity”
Time Frame	“2020” OR “2021” OR “2022” OR “2023” OR “2024” OR “2025”

Example Combined Query (PubMed Adaptation)

(ventilator-associated pneumonia) OR (hospital-acquired pneumonia) OR (nosocomial pneumonia) AND (intensive care unit) OR (ICU) OR (critical care) AND (prevention) OR (infection control) OR (care bundle) OR (subglottic secretion drainage) OR (oral care) OR (chlorhexidine) OR (antimicrobe

Each database was adjusted to search strings to consider differences in indexing and syntax. Moreover, reference lists of used studies, applicable clinical guidelines, and international recommendations (e.g., SHEA/IDSA 2022, CDC, WHO) were hand screened to find additional sources [7,15].

This methodology made sure that both quantitative and qualitative evidence was covered, and a broad range of research designs, intervention strategies, and implementation research was covered that is applicable to the topic of ICU nosocomial pneumonia prevention [15,16].

2.4 Inclusion and Exclusion Criteria

Strict inclusion and exclusion criteria were uniformly applied in ensuring that the literature review was on current, pertinent, and rigorous sources. These were the criteria that served as a guideline because it was able to narrow down the studies to ensure that the synthesis was not only thorough but also the results produced would be applicable to the realities on the ICU infection prevention [7].

Inclusion Criteria

Studies were embraced if they satisfied the following mandates:

1. The publication is between the years 2020-2025 (including the new knowledge and the experience of the pandemic period).
2. Systematic reviews, meta-analyses, peer-reviewed journal articles or globally recognized clinical guidelines.
3. Specifically aimed at the adult ICU groups (more than 18 years) of the crucible of critical care units.
4. Known interventions to prevent or manage nosocomial pneumonia, such as the confusing ventilator-associated pneumonia (VAP).

5. Quantitative results include incidence rates, mortality rates, length of stay at the ICU or the threat of antimicrobial resistance or qualitative data regarding the execution of preventive measures.
6. Published in the English language.

Exclusion Criteria

Conversely, studies were set aside if they stumbled on any of the following barriers:

1. Released before 2020, so as to ensure uncompromising applicability to the current ICU practices.
2. Specialized in the special needs of pediatric or neonatal ICU.
3. Treatment or therapeutic management though not casting light on prevention or control measures.
4. It was composed of case reports, letters, editorials, or commentaries that lacked primary or secondary data.
5. Printed in other languages besides English.

These carefully adjusted and filtered criteria ensured that the literature that was included was directly relevant to adult ICU practice as well as laser focused on preventive and control measures, and that they were thoroughly accepted to the methodological requirements that are supported in infection prevention research. Combining the latest research with the traditional literature published since 2020, the review captures the current trends as well as the groundwork of the current struggle against nosocomial pneumonia.

2.5 Limitations of the Literature Search

- The time limitation to 2020-2025 might have missed significant previous reports that have built the evidence before. Only when this implies the necessity to provide context, these are mentioned.
- The language restriction to English may have missed some regional literature, although guideline documents from international agencies were included.
- Rapid publication and preprints in this field mean some relevant unpublished or non-peer reviewed findings might not have been captured. Peer-reviewed and official guidance documents were prioritized to maintain reliability.
- Heterogeneity in VAP/HAP case definitions and surveillance metrics complicates direct numeric comparison across studies. Definitions were noted when reporting incidence, and guideline updates were used to standardize interpretation.

3. LITERATURE REVIEW

3.1 Definition and Classification of Nosocomial Pneumonia

Nosocomial pneumonia (also known as Hospital-acquired pneumonia (HAP)) is a lower respiratory tract infection, which enters the organism at least 48 hours following the hospitalization of a patient (unless he or she was already infected during the admission) [1,22]. Much of this infection is ventilator-associated pneumonia (VAP) and this is following 48 hours or more of intubation or mechanical ventilation of a patient in intensive care units (ICUs) [2]. The Centers of Disease Control and Prevention (CDC) and the National Healthcare Safety Network (NHSN) differentiate two major groups into which nosocomial pneumonia can be categorized [22].

- Non-ventilator-associated hospital-acquired pneumonia (nvHAP).
- Ventilator-associated pneumonia (VAP).

Both forms contribute substantially to hospital morbidity and mortality, but VAP remains the predominant type in ICU settings due to invasive airway management [8,23].

- Ventilator-associated events (VAE), a broader category that includes infection-related ventilator-associated complications (IVAC) and possible pneumonia. [7].

Recent change in the CDC and NHSN has brought the nomenclature- Ventilator-Associated Event- (VAE) as a broader surveillance approach [7]. These are Ventilator-Associated Conditions (VAC), Infection-related Ventilator-Associated Complications (IVAC) and Possible VAP (PVAP) [7]. The purpose of the layered system is to improve the accuracy of the diagnosis and reduce subjectivity in the detection of VAP because of the difficulty of variability in clinical and radiological tests [24,16]. Proper classification is both essential to surveillance and benchmarking as well as to the application of specific prevention. Misclassification can either underestimate the rate of infection or cause wrong interventions [16].

3.2 Pathophysiology and Microbiological Aspects

Nosocomial pneumonia among the ICU patients is the result of compromised host defenses, virulent microbes, and procedures associated with the ICU [2,24]. In ventilated patients, the endotracheal tube (ETT) circumvents the body's natural mechanisms of clearing the airway like coughing and mucociliary clearance and poses a short circuit to the lower respiratory tract. The biofilms created on the inner surfaces of the ETT act as reservoir of antibiotic

resistant microorganisms and they help in further development of infection [25,24]. One of the major pathogenic mechanisms is micro aspiration of the secretions that accumulate over the ETT cuff. These excretions usually comprise oropharyngeal flora and gastric fluids, which can be introduced into the lower respiratory tract during usual management, repositioning or suctioning [2]. Such issues like sedation, lying flat and prolonged mechanical ventilation increase the chance of aspiration and subsequent infection. Other risks, including immune system imbalances and extended respiratory support, were also presented by the COVID-19 pandemic and further susceptibility to secondary bacterial infections was established [4,6].

Microbiological Profile

The recent literature (2020 - 2025) indicates Gram-negative bacilli as the most common pathogen of ICU acquired pneumonia [9,24]. The typical causative organisms are *Pseudomonas aeruginosa*, *Acinetobacter baumannii* and *Klebsiella pneumoniae* which is typically multi drug-resistant (MDR) [9,10]. Of great importance is also Gram-positive pathogens, particularly, the, (MRSA) pathogens [2,23]. The multicenter comparison of low-and high-income ICUs revealed a high prevalence of MDR pathogens and VAP rates in

resource-constrained settings because of the gaps in ventilator bundles adherence, workforce constraints, and irregularities in antimicrobial stewardship practices [19,11].

Biofilm Formation and Antimicrobial Resistance

The presence of biofilm on ETTs and any other invasive device is essential in the persistence of infections [25]. In biofilm, bacteria are highly resistant to antibiotics, and in most cases, they survive despite sufficient treatment [25]. Free floating biofilm fragments may re-infect distal airways leading to repeat episodes of infection [24]. Carbapenem resistant *Acinetobacter* and *Klebsiella* species are identified by the WHO as critical priority pathogens and prevention stands out as a primary measure against treatment [26].

Host Immune Factors and Lung Microbiome

The host immune condition is a key determinant of vulnerability to nosocomial pneumonia [4,24]. The patients who are critically ill usually show poor leukocyte performance, dysregulated cytokine, and changes in alveolar macrophages functioning that enable bacterial settlement and intrusion [4]. This emphasis risk factors in the development of pneumonia in patients already colonized by CRAB, with the multisite colonization and immunosuppressive

therapy playing a significant role in the development of pneumonia [27]. New studies also note the contribution of the lung microbiome where reduced diversity of microbes and an excess of pathogenic species correlates with increased risk of VAP and increased ICU hospitalization [28]. This is explored that the effect of long-term invasive mechanical ventilation on lung microbiota results decreased diversity and augmented gram negative bacterium and fungal colonization that can predispose the patients to VAP [28].

3.3 Risk Factors Among ICU Patients

A complex interaction of patient-related, device-related, and organizational risk factors is the cause of the multifactorial pathogenesis of nosocomial pneumonia and in particular ventilator associated pneumonia (VAP) in the Intensive Care Unit (ICU) [29,2]. The latest publications (2020-2025) still contribute to the definition of these risks, showing the importance of the endotracheal tube (ETT) and physiological condition of the patient [29].

3.3.1 Patient-Related and Comorbidity Factors

Severely ill patients are at higher risk of developing VAP because of several underlying factors. The data suggests that being male, of advanced age and having COPD are frequently associated with higher risks [29]. When the neurological functioning is impaired, as in the case of people with a lower consciousness or a low Glasgow Coma Scale score, the danger is increased. This is mainly because of the reduced capacity to adequately protect the airway, hence the likelihood of aspiration [2,29].

There is also the influence of metabolic and nutritional status. According to a 2025 study, a BMI within the overweight range (25-29.9 kg/m²) is a major risk factor of developing VAP in severely ill patients of COVID-19 (OR = 4.76) [30]. There are also other complications such as diabetes, multiple organ issues and a weakened immune system which complicates the body to get rid of any infection [10].

3.3.2 Device-Related and Procedural Factors

The endotracheal tube (ETT) is a major risk factor for VAP because it interferes with the body's natural defenses [2,24]. Key mechanisms include:

1. **Biofilm Formation:** Within a short period of time, bacteria develop a biofilm on the ETT, which provides protection to the microorganisms that may detach and enter into the lungs [25,24].
2. **Micro aspiration:** ETT cuff Secretions may leak into the surrounding area causing minute quantities of contaminated material to be inhaled [2].

3. Impaired Clearance: The ETT complicates coughing and clearance of pathogens which increases the risk of infection [2]

The longer a patient requires mechanical ventilator, the more the risk of VAP particularly after a week [33]. The other procedural aspects that enhance the risk are re intubation, tracheostomy, some drugs, such as H2 blockers and sedatives, and enteral feeding that may raise the chances of aspiration and reflux [2,31].

3.3.3 Environmental and Care-Related Factors

The ICU environment and common medical procedures can inadvertently increase the risk of VAP.

Patient Positioning: The supine position is a known risk factor because it makes it easier for stomach and throat content to enter the lungs [32].

On the other hand, a study in 2025 found that the prone position, which was frequently used during the COVID-19 pandemic, was also linked to a higher risk of VAP, highlighting the need for careful attention to patient positioning [5].

Length of Stay and Injury: A longer stay in the ICU and the presence of pressure sores were identified as independent risk factors in a recent study, suggesting that a patient's overall decline and increased exposure to the hospital environment make them more vulnerable [33].

Prior Treatment: Prior antibiotic use and a positive tracheal aspirate before the onset of VAP are significant risk factors, indicating a pre-existing state of colonization or microbial imbalance [10,27].

3.4 Preventive Strategies

The prevention of VAP is based on the consistent use of a team approach involving the proven strategies, which are frequently formed in a VAP care bundle [34,12]. The effectiveness of this approach is supported by recent analyses, where the evidence of certain elements, such as oral hygiene, is continuously increasing [12,35].

3.4.1 Infection Control and Hand Hygiene

Basic infection control techniques, especially hand hygiene, have been the only measure that is most effective with regards to prevention of spread of healthcare-associated pathogens, including those that cause VAP [36,26].

The Indispensable Role of Hand Hygiene

The issue of hand hygiene is extremely significant and must be included in the prevention strategy to prevent VAP. Recent research claims the following:

- **Effectiveness:** By simply learning how to wash hands better we can reduce the transmission of germs by up to half. With increased washing of hands, there is decreased VAP [26].
- **Compliance Problems:** Although hand hygiene is mandatory, it is difficult to comply, particularly in the ICU where there is a lot of activity. In 2025, researchers found that nurses adhered to VAP guidelines 69% of the time, and the adherence decreased with the duration of patient stay [17].
- **Strategy:** World Health Organization (WHO) continues to promote its 5 Moments of Hand Hygiene as the norm. To make people wash their hands more frequently, we should check and provide feedback as well as educate people on how to do it properly [26].

General Infection Control

Basic infection control is important besides hand washing. It is an action of taking very good care of things that enter the body, maintaining an environment and proper use of PPEs [10]. In 2024, one study revealed that an easy prevention strategy, including a handwashing check, actually reduced early VAP in heart surgery patients. This is an indication of the effectiveness of closely following actions that are well-focused [38].

3.4.2 Ventilator-Associated Pneumonia (VAP) Bundles

The VAP bundle is a structured set of evidence-based practices, which, when performed collectively and reliably, have been shown to significantly reduce VAP incidence [12,7].

Efficacy of the VAP Bundle

Recent reviews show that using a bundled approach really works:

Quantitative Reduction: The 2025 analysis of seven studies showed that using VAP bundles led to a substantial improvement, reducing VAP case by 40% [17].

Implementation: This is because sticking to the plan and adapting the bundle to the local situation can be very important in how it works. There is a reduction in the rates of VAP in certain rich countries, whereas they are still higher in poorer countries, in many cases, due to the lack of resources and compliance with the rules [19,39]

Core Components of the VAP Bundle

The core components of a VAP bundle are generally consistent across major guidelines (e.g., CDC, SHEA/IDSA), focusing on reducing aspiration, maintaining ETT integrity, and minimizing the sedation [7,22]:

Head-of-Bed Elevation: Positioning the head of the bed at 30 to 45 degrees in order to avoid the aspiration of gastric and oropharyngeal secretions [32,40].

Daily Sedation Interruption and Weaning Assessment: Sedation holidays and spontaneous breathing trials (SBTs) play a key role in the reduction of the time of mechanical ventilation, which is one of the primary risk factors [44].

Peptic Ulcer Disease (PUD) Prophylaxis: There were no indications of using non-acid suppressing agents (e.g., sucralfate) or reducing prophylaxis to avoid bacteria overgrowth in the stomach.

Deep Venous Thrombosis (DVT) Prophylaxis: Included as a general critical care quality measure.

3.4.3 Oral Care and Subglottic Secretion Drainage (SSD)

Overview and Mechanistic Rationale

Oral care and subglottic secretion drainage (SSD) target two principal mechanistic pathways to ventilator associated pneumonia (VAP): colonization of the oropharynx and pooling of secretions above the endotracheal tube (ETT) cuff with subsequent micro aspiration [2,7]. Oral care reduces bacterial load in the oral cavity and oropharynx, while SSD physically removes secretions that accumulate in the subglottic space and would otherwise leak past the cuff into the lower airways [35]. Both interventions therefore aim to reduce the inoculum delivered to the distal lung a key step in the pathogenesis of VAP.

Evidence Base Oral Care

1. **Toothbrushing and Plaque Removal:** According to recent research, routine dental cleaning can reduce hospital-acquired pneumonia (HAP), which may decrease mortality in ICU and the duration required by patients on mechanical ventilators. A study conducted in 2020 - 2025 connects tooth cleaning daily to the reduction of pneumonia and promotes the idea of regular oral care as an easy and harmless intervention [2,35]. Toothbrushing is

beneficial as it dislodges the dental plaque and decreases the amount of bad respiratory germs in the mouth [35].

2. **Chlorhexidine (CHX) Antisepsis:** Though chlorhexidine gluconate (0.12–2.0%) levels have been widely applied to cleanse the mouths of ventilated patients, the recent studies lessen the results contradicting the earlier ones and elicit safety concern [13,7]. A 2022 study still demonstrated that CHX had the ability to decrease VAP, although subsequent reviews cast its usefulness in doubt and suggested that in certain situations, it might be associated with increased mortality, necessitating selective use of CHX [7,13,35].

Combined/Comparative Approaches: According to meta-analyses and trials conducted in 2020–2025 combination of toothbrushing and antiseptic treatment (such as CHX rinse, wipe, povidone-iodine, or saline) can be more effective than antiseptic treatment in reducing oral germs and in some cases, in reducing VAP [35]. Nevertheless, it is difficult to draw strong conclusions due to the differences in the methods of study. These reviews indicate that mechanical plaque elimination is always useful.

In Intensive Care Unit (ICU), oral care interventions ought to be mainly pivoted on mechanical toothbrushing as a matter-of-course procedure, with moderate evidence, a positive benefit to risk ratio, and cost efficiency [35]. The use of antiseptic agents, especially chlorhexidine (CHX), requires special attention to the issues of concentration, regularity of use, and variables of a patient, as the effectiveness of antiseptic agents and possible safety are not always consistent [41,13]. Antiseptics are usually used along with mechanical toothbrushing, but not alone, when added to oral hygiene regimes. Frequent and proper implementation is critical to achieving successful outcomes in terms of frequency, technique and documentation of all procedures.

Evidence Base - Subglottic Secretion Drainage (SSD)

Subglottic Secretion Drainage (SSD) is an intervention that has always proven effective in prevention of ventilator associated pneumonia (VAP), backed by many randomized controlled trials (RCTs) and meta-analysis [7,15]. Preliminary research showed that SSD decreases the occurrence of VAP, especially the early-onset VAP, by inhibiting the occurrence of micro aspiration. Later studies of 2020-2025 have narrowed down methods, including continuous/intermittent drainage, and volume-based interventions, in which comparable VAP reductions are achieved by better standardization of protocols. A recent RCT that has been mentioned showed the effectiveness of a volume-based personalized approach to SSD in decreasing the rates of VAP and advocated the individualized management approach as

effective and aimed at maximizing these outcomes and minimizing complications [14]. Implementing SSD necessitates the use of endotracheal tubes (ETTs) featuring a subglottic drainage lumen and adequate suctioning regimens, adequate cuff pressure control and head of-bed elevation. The continuous low pressure drainage could be even more effective in stopping secretion build up than intermittent SSD, but they both decrease VAP in relation to no SSD. Another study mentioned in 2025 found that the rate of early-onset VAP decreased significantly when subglottic secretions ports were introduced [43]. The number needed to treat (NNT) was calculated at 10.49, meaning approximately 11 patients needed to be fitted with the device to prevent one case of VAP [46]. This intervention directly deals with the pathway of micro aspiration which is one of the dominant routes of developing VAP [2].

In spite of the good evidence, SSD is not well exploited particularly in resource-denied contexts because there is an increased cost of ETT and resource shortages. The cost effectiveness is determined by the level of VAP in the baseline and higher economic gains in the unit with higher rates [5]. Recommendations suggest SSD should be given to those patients who are supposed to be on ventilation long (e.g. >48-72 hours). SSD is an expensive intervention that can be used to decrease the incidence of VAP, especially in patients who are likely to experience prolonged mechanical ventilation. SSD should be used hand in hand with cuff-pressure measuring and rigorous suction procedure with cost benefit analysis done locally before its universal application. Recent research has shown that mechanical oral hygiene (brushing of the teeth), customized use of antiseptics, and SSD used as part of ventilator bundles lead to more significant changes in the occurrence of VAP than individually, when compliance is good. Implementation science focuses on the significance of training, documentation and audit/feedback to maintain combined interventions.

3.4.4 Patient Positioning and Sedation Management

Head-of-Bed Elevation and Semi-recumbent Positioning

1. **Rationale:** Semi recumbent positioning (elevation of the head-of-bed [HOB]) to 30-45 degrees lessens gastroesophageal reflux and gastric secretions and oropharyngeal secretions aspiration, which reduces the risk of VAP. This is a basic mechanical action that decreases the gravitational flow of secretions to the airway and is advised by significant guidelines as one of the fundamental preventive components.
2. **Evidence:** Systematic reviews and guideline evidence up to and including 2020–2025 consistently support HOB elevation as a low-cost, effective intervention to reduce aspiration and VAP incidence. The AHRQ technical review summarizes that semi

recumbent positioning is associated with decreased aspiration and VAP and is unanimously recommended by leading guidelines [32]. Recent implementation studies (2020-2025) report inconsistent use of HOB targets in routine practice, as well as quality improvement interventions, which involved engineering solutions or automated bed-angle surveillance, had better adherence and reduced aspiration-related events [38,46].

- 3. Practical Considerations & Limitations:** Achieving consistent HOB elevation can be challenging in patients with hemodynamic instability, spinal precautions, or those requiring prone positioning. Monitoring and documentation of bed angle, nursing education, and incorporation into electronic checklists improve adherence. There is also evidence that lower elevations (20–30°) may be better tolerated in some patients while still providing benefit, but 30° is commonly cited as the target.

Prone Positioning – Implications for VAP Risk and Management

- 1. Context:** Prone ventilation is a life-saving option in severe ARDS (including COVID19 ARDS) and is linked to better oxygenation and death rates in specific patients. Nonetheless, prone positioning alters airway dynamics and nursing practice and could affect patterns of secretion clearance.
- 2. Effects on Aspiration and VAP:** The direct impact of prone positioning on the occurrence of VAP is unclear and contradictory. Prone positioning increases the difficulty of performing routine oral and SSD care and clearance of secretions; transient rises in ventilator-associated events have been reported when the volumes of prone positioning were large, but are confounded by the severity of the disease. In general, prone therapy is still recommended even in cases of severe hypoxemia even in the face of procedural complexity; in the process of proning, teams need to pay even greater attention to oral care, suctioning, cuff pressures, and tube fixation to reduce the risk of infections.

Sedation Management, Daily Assessment and Early Mobilization

To cut down on ventilator-associated pneumonia (VAP), we can try to reduce how long patients need to be on a ventilator. This can be done by briefly stopping sedation each day, letting patients try to breathe on their own, following specific plans for taking them off the ventilator, and getting them moving early. Studies show that using less sedation and following weaning protocols can shorten the time spent on a ventilator and in the ICU, which in turn lowers the risk of VAP [7,41]. The best results come from combining these weaning methods with other preventive measures. Getting patients moving early also helps with their breathing,

makes them cough better, and clears out secretions, which reduces the risk of both ICU related weakness and VAP. Recent research supports including early mobility in VAP prevention programs [47,48].

Cuff Pressure Management and Circuit Discipline

Cuff Pressure: Optimal pressure in ETT cuff prevents micro aspiration and minimizes leakage of subglottic content. New suggestions include regular measurements and automated continuous cuff-pressure controllers to control optimum pressure [7,15].

Circuit Management and Humidification: Reduction of circuit breaking, cleanliness of the humidifier, and proper suctioning measures reduce the contamination of devices. Recent outbreak reports and reviews recommend strict maintenance protocols, closed suction systems and single use nebulizers as the best way to mitigate risk of exposure [2,49].

Enteral Feeding, Reflux Prophylaxis and Aspiration Precautions

- 1. Enteral Feeding and Positioning:** Enteral nutrition is standard in critically ill patients but increases reflux/aspiration risk if not managed with positioning and protocols. Elevating the head of the bed and managing aspiration are key strategies to reduce reflux and its associated risks. [2,7]. Current practice emphasizes bedside checks, residual monitoring (with understanding of controversies around its predictive value) and cautious advancement to reduce aspiration risk.
- 2. Acid-Suppression Therapy:** Acid suppression (H2 blockers, PIs) reduces upper GI acidity but may increase risk of colonization with gram-negative bacteria and has been associated with higher pneumonia risk in some studies. Recent guidance recommends judicious use of stress ulcer prophylaxis and limiting acid suppression to patients with clear indications

Staffing, Protocols and Surge Readiness

Organizational preparedness: adequate nurse staffing, training for proning and device handling, clear protocols for positioning and secretion management is crucial. Surge conditions (e.g., COVID-19 waves) highlighted that staffing shortages and rapid cohorting can erode adherence to positioning and suctioning protocols, associated with higher VAP/VAE rates; thus, resilience planning and standard operating procedures are key components of patient-management prevention strategies [19,6].

3.4.5 Antimicrobial Stewardship

Rationale: Why Antimicrobial Stewardship (AMS) Matters for Prevention

Antimicrobial stewardship (AMS) has been described as a method to maximize therapy once an infection has occurred, yet modern evidence has shown that AMS also plays an important preventive effect in ICUs. Stewardship lowers the selection pressure of multi-drug resistant organisms (MDROs) that are the common causes of nosocomial (including ventilator associated) pneumonia (VAP) by decreasing unnecessary exposure or prolonged exposure to antibiotics [50]. Diagnostic stewardship (improving the quality and interpretation of lower respiratory tract sampling and culture reporting) and optimized empirical prescribing can limit inappropriate broad-spectrum antibiotic use, thereby lowering the baseline prevalence of resistant organisms in the ICU ecological niche. These ecological changes translate into lower risk that colonizing flora will be highly resistant and cause difficulty to treat VAP.

Core AMS Interventions Relevant to VAP Prevention

AMS interventions with potential preventive impact fall into several categories:

1. **Diagnostic Stewardship** –improving the quality, timing and interpretation of lower respiratory tract (LRT) sampling (quantitative cultures, protected specimen brushes, bronchoalveolar lavage), and tailoring laboratory reporting to link culture results with clinical criteria so that colonization is not equated with infection. Bundled diagnostic stewardship programs can reduce inappropriate antibiotic initiation for noninfectious ventilator associated events and help stop empiric therapy early when clinical criteria do not support VAP [51,50]. Recent quasi-experimental implementations show this approach reduces antibiotic days and may lower downstream selection pressure.
2. **Treatment Optimization: Short-Course and Individualized Duration** – multiple recent trials and analyses support shorter, individualized antibiotic courses for many ventilator associated and hospital acquired pneumonias when clinical response and biomarkers permit [34]. A 2024 randomized trial and other pragmatic studies demonstrate that individualized, short-course strategies guided by clinical improvement (and, where available, biomarkers) can safely reduce antibiotic exposure without increasing recurrence in many patient groups—thereby lowering cumulative selection pressure in ICUs [34].
3. **Prompt De-escalation and Targeted Therapy** – timely reduction of empiric regimens in response to susceptibility information, or pathogen-directed inhaled antibiotic of specific, high-risk subgroups, lowers broad-spectrum antibiotic days [34]. Embedded stewardship

teams at ICUs have shown a decrease in the total antibiotic use through daily review and direct feedback to prescribing clinicians.

- 4. Antibiotic-Free Preventive Approaches Co-designed with AMS** – strategies like stringent oral care, SSD, cuff management and device care decrease the occurrence of VAP without the use of antibiotics; including them in AMS-led prevention bundles decreases the use of prophylactic antibiotics and promotes stewardship and infection prevention objectives.

Evidence on Upstream (Preventive) Impact of AMS

- **Reduced Colonization with MDROs:** Systematic reviews and narrative syntheses are associated with stewardship programs and the unit level change in patterns of resistance in cases where stewardship effectively decreased the use of unnecessary broad-spectrum antibiotics [50,11]. This is the environmentally relevant effect that will eventually decrease the prevalence of VAP caused by MDROs as a result of stewardship.
- **Diagnostic Stewardship Reduces Unnecessary Initiation:** Quasi-experimental VAP diagnostic stewardship bundles that include standardized sampling, reporting templates and stewardship review have minimized antibiotic days and empiric therapy initiated over noninfectious ventilator events. These interventions may decrease the pressure of antibiotic selection and not multiply the number of missed infections, which is initially promising [51].
- **Shorter Courses Are Safe and Reduce Exposure:** Trials of individualized, shorter antibiotic courses for ICU pneumonias (including recent 2024 randomized data) demonstrate fewer antibiotic days with non-inferior recurrence rates in many patients, supporting duration optimization as an AMS prevention strategy [34].

Practical AMS Recommendations to Support Prevention

1. Integrate stewardship into the daily practice of the ICU (daily antibiotic rounds, prospective audit and feedback) paying attention to early de-escalation and halting rules.
2. Adopt VAP diagnostic stewardship bundles (routine respiratory sampling, routine reporting, review of stewardship before maintenance therapy) particularly at large volume ICUs.
3. Individualized duration strategies, guided by clinical improvement and biomarkers, were validated, to reduce prolonged courses.

4. SDD should be considered under unit-level surveillance and stewardship control at low resistance settings only and when the benefits in VAP reduction have high chances of surpassing the risks of resistance. Keep track of the development of resistance.
5. Integrate AMS with infection-prevention bundles so device and behavioral measures reduce the need for prophylactic or empiric broad-spectrum antibiotics.

Limitations and Unresolved Questions

- There is limited evidence of high-quality RCTs that prove that AMS interventions lower the incidence of VAP (rather than antibiotic use or resistance) most of the evidence is on the ecological or quasi-experimental level [54,50]. There is a need to have more cluster randomized trials and hybrid implementation-effectiveness studies.

3.4.6 Organizational and procedural risk factors

Organizational context and routine procedures shape baseline risk and mediate the effectiveness of technical interventions.

1. Nurse staffing levels and workload:

As evidenced by a number of current studies and reviews, a decreased adherence to prevention bundles and increased rates of device-associated infections, such as VAP, are linked to lower nurse-to-patient ratios and high workload [18,19]. Workers who are overworked do not have time to carry out oral care, cuff checking, and on-time suctioning, which jeopardize prevention. Staffing is one of the structural determinants addressed in implementation studies.

2. Hand hygiene and basic infection-control compliance:

Hand hygiene remains foundational. Recent studies document variable compliance across ICUs and correlate higher compliance with lower VAP rates. Educational programs and multimodal promotion strategies increase adherence but sustaining gains requires continuous audit and feedback [36,26].

3. Bundle composition, fidelity and audit/feedback systems:

Whether or not using ventilator care bundles is effective will not be determined by the simple existence of a checklist, but rather by fidelity: Attention to which elements should be

included, the consistency of their application, and the auditing of compliance feedback. Recent meta-analyses (2023) and implementation reports indicate a heterogeneity in bundle content and variable adoption; in which bundles are integrated into vigorous quality improvement programs (education, monitoring, championing) VAP reductions are greater [12,39].

4. Local surveillance definitions and diagnostic thresholds:

Surveillance and clinical definition variability (clinical VAP vs ventilator-associated events [VAE] surveillance) have an impact on reported rates and may create an incentive to game the definition in case measurement is performance-based. The methodological reviews (2024) point to the fact that organizational inclination on insensitive or inconsistent definitions may conceal the actual incidence as well as block specific prevention. Unified surveillance and standardized definitions are thus very important factors in an organization [16,9].

5. Antimicrobial stewardship programs (ASP):

Organizational ASPs can affect the microbial ecology of ICUs through the mechanisms of supporting empiric and definitive antibiotic selection and reducing unwarranted exposure. Current reports underline that active ASPs decrease the selective pressure on MDR pathogens that cause VAP and ought to be incorporated with preventive measures [11,50].

6. Education, training and culture of safety:

Specialized training that enhances knowledge and short-term practice should be provided to nurses, respiratory therapists, and physicians, and the enhancement should continue with introducing prevention into the unit, leadership, and culture. continuing education. A number of implementation studies published in 2020-2025 associate structured training programs and better bundle adherence and reduced incidence of VAP [54,39].

7. ICU overcrowding, patient turnover and surge conditions:

High occupancy rates, staff redeployment (e.g., during pandemic surges) and supply shortages are associated with increases in VAP rates, which are reported at COVID-19 waves [6]. Planning on organizational resilience (stockpiles, cross-training, surge protocols) can reduce risk but costs need to be proactively invested.

8. Policy and resource constraints in LMICs:

Limitation of resources (insufficient number of SSD-compatible tubes, fewer cuff-pressure devices, less access to disposable suction catheters, etc.) also puts people in most LMIC environments at a greater risk of developing VAP [5]. The implementation research in such settings underscores the need to focus on low-cost and high-yield practices (head-of-bed elevation, basic oral care, hand hygiene) and recommends step-by-step implementation of more resource-intensive technologies.

3.4.7 Vaccination and immunomodulation strategies

Vaccination lowers the frequency and the severity of vaccine-preventable respiratory viral and bacterial infections which are significant antecedents to critical illness and secondary bacterial pneumonia. In prevention of nosocomial pneumonia particularly in ICU this is important in the following ways:

- **Primary prevention:** Influenza, pneumococcal, and (more recently) RSV vaccines minimize the population of patients with severe community-acquired respiratory diseases that necessitate ICU-care, thus lessening the reservoir of critically ill patients in high-risk group of secondary nosocomial pneumonia [55,56].
- **Secondary prevention of bacterial superinfection:** influenza vaccine lowers the rate and severity of influenza and thus the risk of bacterial superinfection (e.g., pneumococcal and staphylococcal pneumonia) to complicate ICU hospitalization [57]. This protective cascade is supported by observational evidence and mechanism studies.
- **Indirect benefit for the ICU ecology:** an increased share of vaccinated patients and staff members decreases the pressure of the transmission of respiratory pathogens in hospitals, which in turn, indirectly decreases the risk of nosocomial acquisition [57].

Contemporary evidence on vaccine impact

Pneumococcal vaccines: Recent cohort and population studies show that pneumococcal conjugate and polysaccharide vaccines may reduce hospitalization rates of pneumonia due to pneumococci and may reduce in-hospital mortality in adults. Newer adult advice (e.g., revised ACIP/CDC advice in late 2024) is based on changing evidence and newer conjugate preparations that extend serotype coverage [56]. Though the majority of primary vaccine trials involve the community-acquired disease, the downstream effect reduced case of severe pneumococcal pneumonias and ICU admission, or secondary nosocomial infections- is viable and corroborated by the population studies.

Influenza vaccination: Systematic reviews and surveillance data show that annual influenza vaccination will decrease hospitalization of influenza and severe disease. Lessening the cases of influenza reduces the number of secondary bacterial pneumonias or ICU re admissions and thus reduces the chances of nosocomial pneumonia [57]. More recent recommendations also highlight the importance of high dose/ adjuvanted vaccines when used in older and high risk adults.

RSV vaccination and monoclonal antibodies (2023-2024 licensing era): New opportunities are offered by the recent licensure (2023) and release of adult RSV vaccines (several products approved by 2023-2024) and long-acting monoclonal antibodies to prevent the severe RSV disease, which is a significant cause of respiratory hospitalization in older adults and infants. An initial effectiveness data, 2023-2024 season, indicates significant decrease in hospitalizations related to RSV in the elderly-this can indirectly lower ICU hospitalizations and downstream risk of nosocomial pneumonia in highly circulating seasons of RSV [55].

Practical implications of vaccination for ICU nosocomial pneumonia prevention

1. **Patient vaccination programs:** Hospitals should focus on pneumococcal and influenza vaccination of inpatients upon discharge and opportunistically vaccinate eligible patients in both outpatient and inpatient settings to prevent further severe respiratory illness and the subsequent workload on ICU. This preventive horizon reduces the risk of the population that causes nosocomial pneumonias in ICU. [56,57].

2. **Staff vaccination:** Health care worker vaccination (seasonal influenza, now influenza plus COVID/RSV where recommended) helps mitigate the risk of staff-to-patient transmission and workforce capacity in seasonal surges-a pragmatic infection-prevention intervention with system resilience benefits [57].

Immunomodulation and VAP risk

Rationale: Systemic immunomodulators, especially corticosteroids, represent an integral part of the treatment of such conditions as ARDS, or septic shock. Nevertheless, they may inhibit host defense and therefore, the chances of secondary infections, such as VAP, may rise.

Evidence and trade-offs:

- **Corticosteroids:** Certain studies have concluded that the use of systemic corticosteroids in patients who are critically ill, over prolonged periods or in high doses, predispose patients to VAP, particularly in non-COVID-19 ARDS. However, with such illnesses as

severe COVID-19 and early ARDS the risk of VAP is not as high as the benefit of corticosteroids. The trick is in moderation: minimal dose of medication within the minimum period.

- **Other agents:** Other immunomodulatory agents (e.g., biologics, antivirals) can also have effects on the risk of VAP, although the effect is strongly situation-specific because it may be positive or negative [24,15]]. They include underlying illness, agent type and dosage, duration of treatment and individual patient factors.
- **Clinical implication:** Immunomodulation is a two-sided sword. Although this is a vital part of the treatment of the initial critical disease, the risk of VAP should be

proactively addressed by the increased use of infection prevention bundles (e.g., oral care, early mobility) in systemically immunosuppressed patients [7,41].

3.5 Emerging technologies and future prevention trends

There is an increasing collaboration in new strategies of preventing hospital-acquired pneumonia in ICU [1,2]. In addition to the common interventions, recent research is investigating approaches that could address the microbiome (such as probiotics), medical equipment improvements (such as closed suction systems), and new infection-control tools (such as UV-C disinfection and AI surveillance). I will overview the justification of such approaches, existing research results (efficacy and safety), the way they can be implemented, and unresolved questions.

3.5.1 Use of probiotics or selective digestive decontamination (SDD)

Mechanistic Rationale

Both SDD and probiotics are meant to adjust microbial ecology of the oropharynx and gut so that it decreases the overgrowth of possible pathogens that can seed the lower respiratory tract [28,24].

- Probiotics/Synbiotics suggest replacing or maintaining a beneficial microbiota competing with gram-negative pathogens and *Staphylococcus aureus*, translocation reduction, and adjusting the mucosal immunity [58,28].
- Selective Digestive Decontamination (SDD) involves topical use of non-absorbable orally and gastrointestinal based antibiotics to selectively eliminate potentially pathogenic aerobic Gram-negative microbes, while trying to preserve the anaerobic commensals [52,53].

Evidence Summary

Probiotics/Synbiotics

Systematic reviews and randomized controlled trials provide different results on the use of probiotic prophylaxis in preventing ventilator-associated pneumonia [58]. Whereas there are meta-analyses indicating that the incidences of VAP declined slightly, there are those that show no significant effect with consideration of the heterogeneity of studies and possible bias [58]. Inconsistencies in the quality of the trial, especially with strain diversity, dosage, administration forms, and sample sizes, and a lack of safety information in immunocompromised patients or critically ill patients are noted in reviews published in 2024 [58]. Thus, recent findings indicate possible benefits in certain patient groups but do not provide the absolute need to recommend it to most patients.

Recent randomized controlled trials, either single centered or multi centered, have cited a lower incidence of VAP using specific probiotic preparations. Nevertheless, these are rather small and frequently single-blind studies. The systematic reviews would encourage larger and standardized multi center RCT that makes use of well-characterized strains and regimens to warrant broader adoption [58].

Selective Digestive Decontamination (SDD)

There is solid evidence that supports selective digestive decontamination (SDD) as a microbiome directed intervention [52,53]. Reductions in the incidence of VAP and in some meta-analyses an improved mortality in environments with low baseline antimicrobial resistance have been demonstrated by large randomized controlled trials and pooled analyses up to 2022 [52]. A 2022 systematic review has provided these advantages but noted that resistance surveillance is necessary [52]. More recent reviews and implementation reports indicate that SDD decreases the incidence of VAP and may decrease the overall mortality in many studies. Nevertheless, the contexts of generalizability of mortality benefits depend on the local ecology of resistance and stewardship practices [50,11].

Contemporary narrative and implementation literature emphasizes prudence: SDD can be used in situations where (a) the prevalence of antibiotic resistance is low, (b) stewardship and microbiology surveillance is strong, and (c) there is emerging selection pressure favoring resistance, which is actively monitored. In the absence of such conditions, SDD will create resistance and change unit ecology in the long term. Safety, Ecological and Stewardship considerations.

Safety, Ecological, and Stewardship Considerations

- **Probiotics:** The safety issues are rare incidences of probiotic-associated bacteremia/fungemia in highly immunosuppressed hosts; the selection of strains, product quality, and regulation worldwide [58] Trials do not report many serious adverse events, although systematic reviewers encourage caution in high-risk ICU populations [58].
- **SDD:** The main issue is selection against antimicrobial resistance (e.g., selection of colistin or carbapenem resistance), which might have significant downstream effects [43,24]. A number of surveillance studies emphasize that the unit-level resistance surveillance should be conducted continuously in case of SDD implementation [50]. Long-term resistance increases have not been universal when SDD has been applied in controlled trials with active surveillance, but the heterogeneity of settings requires local evaluation [52,53].

Implementation and Cost-Effectiveness

- Probiotics are cost-effective and easy to administer, but the lack of uniform product range and standard dosing schedules makes it harder to implement. The cost effectiveness is not proven since estimates of clinical benefits are inaccurate [58].
- SDD requires a supply of topical antibiotics and a stewardship/microbiology infrastructure for surveillance; cost-effectiveness analyses in 2023–2024 suggest SDD can be cost saving in higher-income units with high baseline VAP rates and low resistance but may be inappropriate in resource-constrained or high-resistance environments [52,50].

Research Gaps and Priorities

- High-quality multi Centre, large-scale randomized clinical trials of standardized probiotic preparations (strains of microbes, doses, routes, schedules of administration, well-defined patient outcomes) with patient-oriented outcomes (VAP incidence, ventilator-free days, safety) [58].
- In the case of SDD, pragmatic implementation experiments, which involve internal stewardship and long-term resistance monitoring, will assist in identifying situations in which the benefits of the interventions surpass the ecological risk [53,50]. There is a shortage of comparative cost-effectiveness studies in LMICs [5].

3.5.2 Technological innovations (closed suction systems, silver-coated tubes)

Technological Innovations

Closed Tracheal Suction Systems (CTSS) vs Open Suction (OTSS)

Rationale and mechanism: Closed suction systems are intended to allow endotracheal suctioning without disconnecting the patient from the ventilator, and thereby avoiding circuit breaks, preservation of PEEP, minimization of transient hypoxia, and theoretically, elimination of device contamination and aspiration during suctioning [49].

Evidence: Meta-analyses and a few trials released in 2022-2024 provide equivocal evidence. A 2022 pooled analysis established a reduction in the incidence of VAP with CTSS in a number of the trials, but more recent systematic reviews and quasi-experimental studies (2023-2025) found only minor or no difference when other infection control practices are optimal [49]. The quality of studies is heterogeneous and makes interpretation difficult because of the outcome's definitions and underlying practices [16]. Recent 2024-2025 studies still indicate that CTSS might help to minimize cross-contamination and temporary physiological imbalance, but the level of VAP prevention is probably small and conditional [41].

Practical notes: CTSS are costlier than the single-use type of open suction catheters and involve strict maintenance; their advantages are likely to be the most significant in the situations when circuit break is prevalent or instability in oxygenation during the suctioning process occurs [49]. Cost-benefit analysis is location specific [5].

Antimicrobial / Noble-Metal Coated Endotracheal Tubes (ETTs)

Rationale and mechanism: ETT biofilm formation is a persistent reservoir for lower respiratory tract inoculation [25]. The antimicrobial coating of inner/outer surfaces of ETTs with antimicrobial agents (e.g. silver) or noble-metal alloys prevents the adhesion of microbes and biofilm formation, which, in theory, prevents the seeding of bacteria in the lung [33].

Evidence: Earlier RCTs (pre-2020) indicated silver-coated ETTs reduce early VAP incidence. Newer studies (2020–2025) and multicenter evaluations of noble-metal coated tubes report reduced VAP incidence but no consistent effect on mortality or ventilator days [33]. A 2024 multicenter evaluation concluded coated ETTs lower VAP incidence but do not change ICU LOS or mortality; cost and supply considerations remain significant [33]. Several 2024–2025 device comparisons and meta-analyses reaffirmed reduction in colonization and VAP but emphasized heterogeneity of effect sizes and limited scalability data [33].

Implementation and cost: Coated ETTs cost more; when the baseline VAP rates and the costs per VAP episode are high, then the cost-effectiveness is greater [33,51]. The units that

are considering adoption are expected to conduct local economic modeling and can decide to make targeted use of patients that are likely to need a long ventilation.

Other Device Innovations and Adjuncts

- Continuous cuff-pressure controllers and better cuff design; current evidence (2022-2024) indicates that these devices decrease micro aspiration, but RCT evidence of hard clinical outcomes is weaker.
- Closed ventilator circuits, disposable nebulizers, and humidifier design. There is practical evidence (including reports of outbreaks) of decreased contamination of devices when maintenance procedures are taken [59].
- The device innovations (CTSS, coated ETTs, cuff controllers) demonstrate biologic plausibility and consistent reductions in intermediate outcomes (colonization, micro aspiration). The best-evidenced device-level prevention which is SSD; coated ETTs and CTSS show more modest or context dependent benefits [7]. Economic and supply considerations determine feasibility for routine use.

3.5.3 Novel Infection Control Technology (UV, AI-based monitoring)

Ultraviolet-C (UV-C) Room and Surface Disinfection

Mechanism and rationale: UV-C (wavelength ~254 nm) inactivates bacteria, viruses and spores by damaging nucleic acids; automated UV-C systems are used as adjuncts to manual cleaning to reduce environmental bioburden on surfaces and in air [60]. In respiratory pathogens able to persist on fomites or through aerosol transmission, the adjunctive UV-C can eliminate environmental reservoirs.

Evidence (2020–2025): A number of systematic reviews and pragmatic studies (2020-2025) indicate that UV-C room disinfection can result in lower environmental contamination and that in some hospital environments UV-C room disinfection is linked with lower rates of certain HAIs (e.g., *C. difficile*, MRSA) [60]. There is little specific evidence linking consistent use of UV-C to lower VAP occurrence as VAP transmission processes are intricate and usually associated more with device handling and aspiration than with room surface contamination [2,24]. A recent 2023-2025 review finds UV-C is a helpful adjunct to terminal cleaning and can decrease the burden of environmental pathogens; it is plausible but not conclusively shown that regular UV-C implementation can decrease the incidence of nosocomial pneumonia in ICUs [15].

AI-Enabled Surveillance, Monitoring and Compliance Systems

- **Rationale and capabilities:** AI and machine-learning systems are being developed to (a) improve surveillance (HAIs identified automatically in EHR data), (b) identify high-risk patients to guide interventions, and (c) adhere to infection prevention (e.g., automated dispensers of hand hygiene, bed-angle).
- **Evidence (2020–2025):** A pilot study (2023-2025) and early adopter hospitals (2023-2025) report that AI-assisted surveillance is more sensitive to detection and timely compared to traditional manual surveillance and that electronic monitoring systems can enhance hand-hygiene compliance with feedback. Recent 2024-2025 publications demonstrate successful cases of AI models anticipating ventilator-associated events or outbreaks up to weeks prior to conventional detection, and taking preventative action [61]. Nevertheless, the majority of studies published are single-center implementations, and prospective controlled trials proving that AI implementation has a direct effect on the reduction of VAP incidence are still scarce [61].
- **Practical and ethical considerations:** The implementation would need the high quality of EHR data, IT infrastructure, validation on the local populations, false positive (alert fatigue) attention, and data privacy governance [62]. AI models should be open and recalibrated on a regular basis to prevent drift. Clinical workflow integration and well defined mechanisms to escalate to preventive actions are necessary so that predictions could be converted into prevention [61].

Other Digital Adjuncts and Sensors

Electronic hand-hygiene monitoring systems (EHHMS) and bed-angle sensors have demonstrated encouraging results in QI research and improvement of process measures (compliance, HOB elevation) and are associated in some locations with a decrease in device related infections [36,63]. Nevertheless, the direct data on the lower incidence of VAP are still developing and mostly are disrupted by simultaneous bundle programs [12,7].

Bottom line (2020–2025 evidence): UV-C can have a definite use in the decontamination of the environment and the control of outbreaks, but little direct data on the prevention of VAP. AI and electronic monitoring can be promising to improve surveillance and maintain compliance with the processes, but quality trials with clear proof of direct VAP changes are still required [15,61]. Ultimate adoption must involve investment, information infrastructure and prudent change management [47].

Cross-Cutting Considerations for Emerging Approaches

1. Context matters. Absolute and relative value of probiotics, SDD, coated ETTs, UV-C, and AI is based on local baseline VAP rates, antimicrobial-resistance rates, staffing and budgetary limitations [19,20]. Cost-effective interventions used in high-income, high VAP contexts cannot be translated into low-resource contexts [5].
2. Ecologic stewardship (resistance surveillance) is non-negotiable for antibiotic-based preventive strategies. [64,50]. SDD and any prophylactic antibiotic approach require active, continuous microbiologic surveillance to detect and respond to emergent resistance [11].
3. Implementation of science & hybrid trials are needed. For many emerging approaches, evidence is strong for mechanistic plausibility and intermediate outcomes (reduced colonization, environmental bioburden). What is frequently lacking are hybrid effectiveness–implementation trials that measure patient-level outcomes (VAP incidence, ventilator-free days, mortality) and real-world sustainment, cost, and ecological impact [16,15].
4. Risk–benefit, cost and equity. Technology and drug-based prevention strategies can widen inequities if only tertiary centers can afford them [59,19]. A tiered approach is sensible: maximize high-value, low-cost practices universally (hand hygiene, head-of-bed elevation, toothbrushing, SSD where feasible) and consider advanced interventions (SDD, coated ETTs, UV-C, AI) selectively based on local need, capacity, and surveillance capability [7,15].

4. DISCUSSION

4.1 Synthesis of Key Findings

This literature review is a synthesis of the current evidence (2020-2025) on the prevention of nosocomial pneumonia (NP) specifically ventilator-associated pneumonia (VAP) in adult intensive care units (ICUs) [8,2]. The consistent message that is evident through more than a hundred studies, systematic reviews, and updated international guidelines is that nosocomial pneumonia is highly preventable by using a combination of evidence-based clinical practice, antimicrobial stewardship, and organizational commitment.

Key Insights

1. Multifactorial Pathogenesis

Nosocomial pneumonia occurs as a result of interaction of microbial, device related and the host factors [1,2]. Recent literature supports a continuum of colonization to infection instead of a two-event occurrence with micro aspiration, endotracheal tube (ETT) biofilm colonization, and impaired mucosal defense reported as some of the key processes [2,24]. Persistence of biofilm on airway equipment facilitates the survival of bacteria and relapses of the infection that stresses prevention rather than therapy [25,19].

2. Dominant Pathogens and Resistance Trends

Still, the predominant etiological agents include *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Acinetobacter baumannii* gram negative bacilli and *Staphylococcus aureus* gram-positive [20,19]. Multi drug-resistant (MDR) and carbapenem-resistant strains are on the rise in most parts of the globe, although in low- and middle-income countries (LMICs), the prevalence rate is more due to the absence of resources and inadequate stewardship programs [19,11].

3. Validated Preventive Strategies

Evidence consistently supports traditional infection-prevention interventions:

- Core measures are hand hygiene, head-of-bed (HOB) elevation $\geq 30^\circ$, or higher, daily interrupt sedation, oral care (mechanical toothbrushing), and subglottic secretion drainage (SSD) [7,41].
- SSD is the best intervention at the device level as it can decrease the occurrence of VAP by up to 40-50% in several randomized controlled trials and meta-analyses.
- A ventilator care bundle implementation leads to a 20-50% reduction in VAP based on compliance and local modification [12,39].

4. Antimicrobial and Diagnostic Stewardship

Antimicrobial stewardship (AMS) has become a preventive rather than a therapeutic aid. AMS indirectly prevents VAP by lowering colonization pressure and selection of MDR organisms by decreasing unnecessary exposure to antibiotics [50,11] Diagnostic stewardship that enhances the effectiveness of respiratory sampling, culture interpretation, and reporting lowers the use of inappropriate antibiotics in the treatment of non-infectious ventilator associated events [51].

5. Emerging Preventive Innovations

- Probiotics and Selective Digestive Decontamination (SDD): Both alter the intestinal flora to prevent the growth of pathogens. SDD is in use in low-resistance environments where the surveillance is strong but requires the management of stewardship [52,53].
- The technological advances of closed suction systems, silver/noble-metal-coated ETTs, and continuous controllers of cuff-pressure show some degree of reduction in airway colonization and aspiration but are unaffordable and unavailable in LMICs [33,49].
- Digital and AI-powered surveillance systems have some potential in predictive surveillance, detection of early outbreaks, and compliance monitoring, although the evidence is still in its infancy [61,62].

6. Vaccination and Immunomodulation

The indirect effects of increased influenza, pneumococcal and COVID-19 vaccination and the introduction of adult RSV vaccines have decreased the number of ICU admissions and secondary bacterial pneumonias [57,56,55]. These prevention effects are upstream preventative effects, which support the vaccination as a component of the NP-prevention ecosystem.

7. Implementation and Contextualization

Fidelity of implementation, staff involvement, and adaptation to context are what determine the success of any intervention. Research indicates consistently that a high level of compliance with simple, inexpensive interventions (e.g. oral care, HOB elevation) would have higher benefit than the partial adoption of complex technologies [12,7].

In summary:

The recent evidence confirms that NP prevention needs an integrated and multidisciplinary approach that incorporates infection-control, stewardship, and technology. Sustainable enhancement relies upon local circumstances, leadership, and culture, and not on the detached technical interventions.

4.2 Comparison with International Guidelines (CDC, WHO, ECDC)

The given results confirm the high degree of compliance with the most recent recommendations of the main global health agencies: the Centers of Disease Control and

Prevention (CDC, 2022-2023) and World Health Organization (WHO, 2023-2024) and European Centre of Disease Prevention and Control (ECDC, 2022-2024).

Table 5: Comparison with International Guidelines (CDC, WHO, ECDC)

Area of Comparison International Guideline Consensus Evidence)		Review Findings (2020–2025)
Core Preventive Measures	Endorse bundled prevention: Hand hygiene, HOB elevation, daily sedation interruption, oral care, and SSD.	Confirm bundle measures reduce VAP incidence by 20–50% when.
Antimicrobial Stewardship	Essential to prevention; discourages programs unnecessary prophylaxis.	Corroborates that effective AMS reduce MDR colonization and antibiotic selection pressure.
Vaccination	Focuses on influenza and pneumococcal for staff and high risk patients.	Broadens to include COVID-19 and newly licensed RSV vaccines, reducing upstream respiratory disease burden.
Device Management	Recommend maintaining cuff pressure, avoiding circuit breaks, and using SSD capable ETTs.	Confirms these strategies reduce aspiration and early-onset VAP.
Probiotics and SDD	WHO/CDC do not endorse routine use; ECDC permits SDD conditionally in low-resistance settings.	Supports this conditional position, emphasizing strict monitoring for resistance.
Implementation	Surveillance, audit feedback and safety culture are vital.	Strengthens adherence to implementation and incorporation of digital innovation as main frontiers of continued success.

4.3 Gaps in Current Evidence

Despite significant advancements, the evidence from 2020 - 2025 still has some notable gaps that need to be addressed.

1. Heterogeneity of Definitions and Surveillance:

CDC/NHSN and clinical criteria differ in definitions of VAP, making it difficult to benchmark and perform meta-analysis [22,16]. The more recent Ventilator-Associated Event (VAE) structure is more objective but has a risk of the clinically relevant infections being overlooked

2. Limited High-Quality Randomized Trials:

Most of the new interventions (e.g., probiotics, coated ETTs, AI systems) do not have large multi-center RCTs with a standard endpoint (VAP incidence, ventilator-free days, mortality) [33,61].

3. Data Deficit in LMICs:

Most of the intensive research is based on high-income nations, and the largest burden of VAP is in LMICs [5]. There is a dire need to conduct research to respond to local constraints and cost-effectiveness [15]

4. Long-Term Ecological Impact of SDD:

Short-term benefit is well supported by evidence, although not many studies have gone past a month in their investigations on long-term resistance patterns [52,53].

5. Digital and AI-Based Tools:

Initial findings indicate improvements in the processes but little outcome data. The problem of ethical, privacy, and bias needs to be explored [61,62].

6. Vaccination–Prevention Interface:

Although the positive benefits of vaccination are high in the upstream, no studies directly measure the effects of vaccination on the occurrence of nosocomial pneumonia in the ICU [57,56].

7. Behavioral and Cultural Barriers:

The problem of inconsistent staff compliance is one of the barriers [36]. There is under-use of the implementation-science framework especially when it comes to evaluating the effects of culture, workload, and leadership on adherence [38].

4.4 Implications for ICU Practice and Policy

Table 6: ICU Practice and Policy

Area	Implication for Practice and Policy
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Embedding Bundled Prevention	Implementation of ventilator bundles should be highly reliable. Uncomplicated, inexpensive interventions (hand-hygiene, HOB elevation, oral care) should not be compromised. Sustained fidelity requires the use of checklists, audits, and feedback loops.
Integrating Antimicrobial Stewardship	AMS ought to be incorporated in everyday ICU practices. Store rounds should be involved in stewardship pharmacists and infectious-disease specialists to enhance de-escalation and rationalization
Strengthening Surveillance and Feedback	The VAP rates, antibiotic use, and bundle compliance can be monitored in real time with the help of the standardized and continuous surveillance (with the help of CDC/NHSN or ECDC definitions) facilitated by digital dashboards
Context-Adapted Innovation	Low-resource ICUs: Prioritize behavioral and procedural adherence. High resource ICUs: Incorporate SSD, coated ETTs, cuff controllers, and electronic monitoring were cost-effective.
Policy Integration	ICU bundle compliance, AMS programs, and resistance surveillance should be mandatory in the national policies. Digital solutions should be scaled by investing in vaccination coverage and intersectoral collaboration.
Workforce Education and Empowerment	Regular multidisciplinary training strengthens adherence. Empowering nurses and respiratory therapists to monitor and escalate deviations improves long-term compliance.
Research and Quality-Improvement Agenda	Future research should prioritize pragmatic, multicenter trials and hybrid implementation studies. Global consortia, especially inclusive of LMICs, should standardize data sharing and cost-effectiveness frameworks.

5. CONCLUSIONS AND RECOMMENDATION

5.1 Summary of Main Conclusions

This is a literature-based thesis that has synthesized all evidence on the prevention and control of nosocomial pneumonia especially ventilator-associated pneumonia among intensive care unit patients [1,2]. The review established that ventilator associated pneumonia can be

prevented to a large extent when the evidence-based interventions are given with high fidelity and with the backing of the institutional commitment [7,12].

Key conclusions include:

Nosocomial Pneumonia as a Preventable Complication:

Recent research evidence continues to show that the majority of instances of ventilation associated pneumonia, and nosocomial pneumonia can be averted by means of standardized, inter-disciplinary care packages consisting of mechanical, behavioral, and organizational components [15,41].

Proven Core Measures:

Head-of-bed elevation $\geq 30^\circ$, regular oral care with mechanical tooth brushing, subglottic secretions drainage, interrupting daily sedation, and spontaneous breathing trial are the basis of prevention [40,35]. These measures lower the rates of ventilator associated pneumonia by 20-50% when applied systematically [25,12].

Antimicrobial Stewardship as a Preventive Tool:

Antimicrobial stewardship is preventive as well as treatment, and decreased colonization pressure and increased multi drug-resistant organism development is minimized by reducing antibiotic misuse [63,11]. Inappropriate antibiotic exposure is also minimized by diagnostic stewardship [51,34].

Emerging and Adjunct Innovations:

New technologies including coated endotracheal tube, constant control over cuff-pressure, Ultraviolet-C disinfection, and artificial intelligence surveillance have a potential of good adjunctive value [33,61]. Nonetheless, it is expensive and the infrastructure is not available in many low-middle-income countries which limits its application [5]

Vaccination and Immunomodulation:

Nosocomial pneumonia is indirectly prevented by increased vaccination coverage (influenza, pneumococcal, coronavirus disease 2019, respiratory syncytial virus) due to a decrease in upstream respiratory infections [57,56,55]. A reasonable use of immunomodulators (example: corticosteroids) is critical to counteract advantage against higher risk of ventilation associated pneumonia [65].

Contextual and Implementation Factors:

Implementation fidelity the ability to adhere to it consistently, staff involvement, leadership, and safety culture is the strongest determinant of success [46,54]. Poor staffing, lack of training, and effective surveillance are the constant challenges, particularly in Low-middle income countries [18,37].

Global and Policy Alignment:

Results are in line with Centers for disease control and prevention, World Health Organization, and European center for disease and control recommendations, which support the international opinion regarding bundled prevention, AMS integration, vaccination, and surveillance [22,64,7]. Nevertheless, there is still a gap in evidence of heterogeneity of definition, absence of Low-middle-income countries data, and paucity of Randomized controlled trials on novel interventions [16,29].

5.2 Recommendations for Clinical Practice

Based on the evidence synthesized and international guidelines, the following practical suggestions are offered for intensive care unit clinicians, administrators, and policymakers [7,15].

A. Clinical and Procedural Recommendations

1. Ventilator Care Bundles

Have high-fidelity ventilator bundles that include:

- Head-of-bed elevation $\geq 30^\circ$ [40].
- Breaks and spontaneous breathing trials: daily sedation [2]
- Early mobilization
- Oral hygiene with toothbrushing $\pm$ antiseptics (as locally appropriate) [35,13].
- Subglottic secretion drains for patients ventilated >48 –72 hours [14,42].
- Compliance should be checked with the help of checklists, real-time audit and feedback [39,38].

2. Antimicrobial and Diagnostic Stewardship

- Make use of diagnostic stewardship to identify colonization versus actual infection [51].

- Integrate anti-microbial stewardships teams into the routine rounds of the intensive care unit [11,50].
- Take short and personalized courses of antibiotics under the direction of the biomarkers and innovations [34].
- Restrict prophylaxis (example. Selective decontamination of the digestive tract) to low resistance settings where active surveillance is performed [52,53].

3. Device and Environmental Management

- Keep constant pressure of cuffs; do not have inappropriate circuit breaks [20].
- Use closed suction and close circuit-handling measures [49].
- In the case of coated endotracheal tube, take into account continuous pressure controllers, which are cost-effective [33].
- The monitoring of ultraviolet-C or artificial intelligence should only be used where the infrastructure and cost are justified [61].

4. Vaccination and Immunization

- Implement high-risk patient and healthcare worker influenza, pneumococcal, disease 2019 and respiratory syncytial virus vaccination [57,55].
- During discharge and outpatient programs, integrate vaccination as a way of decreasing upstream intensive care unit admissions [64].

5. Staffing, Education, and Safety Culture

- Maintain a sufficient nurse to patient ratio to support bundles [18].
- Carry out multidisciplinary training based on infection prevention, surveillance, and communication [36].
- Promote a just culture where reporting and continual improvement is encouraged.

B. System and Policy Recommendations

1. Surveillance and Data System

- Standardization of the definitions of surveillance (Centers for disease control and prevention/National healthcare safety network or European center for disease and control) to benchmark [22,16].

- Use electronic dashboards or artificial intelligence -based tools in real-time ventilator associated pneumonia monitoring and compliance [61,62].

2. Policy Integration

- Mandate compliance of ventilator bundle and anti-microbial stewardship programs and resistance surveillance in hospital accreditation standards [64,15].
- Make intersectoral collaboration (healthcare, informatics, engineering) in favor of digital infection prevention tools [62].

3. Resource Adapted Strategies

- Low-resource intensive care units: Focus on simple intervention methods, including HOB elevation, hand hygiene, oral care, and training staff [59,26].
- High-resource intensive care units: Combine new technologies (Subglottic secretion drainage, coated tubes, artificial intelligence analytics) and robust stewardship management [33,61].

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ARTIFICIAL INTELLIGENCE DISCLOSURE

AI Tool Used: ChatGPT (OpenAI)

Purpose and Scope of Use

In completing this thesis, I used OpenAI's ChatGPT as a supportive tool for research guidance, editing, and overall refinement of the work. The tool assisted in the following key areas:

1. Research Exploration and Literature Discovery

ChatGPT was used to help identify relevant academic themes and potential studies related to the prevention and management of nosocomial pneumonia, including ventilator-associated pneumonia (VAP), infection control practices, antimicrobial stewardship, and hospital hygiene protocols.

For instance, I prompted ChatGPT with a sample statement such as:

“Nosocomial pneumonia, particularly ventilator-associated pneumonia, remains a major cause of morbidity in hospitalized patients. Please suggest relevant studies or research areas that support effective prevention strategies.”

ChatGPT generated several potential sources and thematic directions. I then independently searched for these studies using academic databases such as PubMed, Cochrane library, Google Scholar and institutional library resources, where I identified credible and relevant literature for formal citation. In some cases, ChatGPT helped narrow down broader topics into more focused areas for deeper analysis.

1. Final Review and Language Polishing

I used ChatGPT to conduct a comprehensive review of the thesis for clarity, coherence, and grammatical accuracy. Key areas of assistance included:

- **Clarity and Coherence:** Identification of weak transitions or gaps in logical flow between sections (e.g., linking prevention strategies to clinical outcomes)
- **Grammar and Conciseness:** Correction of minor grammatical errors and reduction of repetitive phrasing
- **Terminology Consistency:** Standardization of key terms such as “nosocomial pneumonia,” “hospital-acquired pneumonia,” and “ventilator-associated pneumonia”
- **Citation Consistency:** Assistance in ensuring uniform formatting of references

All revisions were implemented manually after careful evaluation to ensure they aligned with the scientific intent and academic tone of the thesis.

2. Section Structure Support

While I retained full authorship and editorial control, ChatGPT was used to help structure early versions of selected components, including:

- **Prevention Frameworks:** Generated initial outlines for infection prevention strategies such as hand hygiene, ventilator care bundles, and antibiotic stewardship
- **Clinical Explanations:** Assisted in structuring general explanations of disease mechanisms and risk factors

All drafted content was substantially revised, validated with peer-reviewed sources, and aligned with established clinical guidelines.

Sections Where ChatGPT Was Not Used

Notably, ChatGPT was not relied upon in developing the core scientific and analytical components of this thesis. These include:

- Data analysis and interpretation
- Critical evaluation of findings
- Clinical reasoning and conclusions
- Integration of evidence into final arguments

These sections were developed independently to ensure accuracy, originality, and scientific rigor.

Human Oversight and Final Ownership

All outputs from ChatGPT were used strictly as supportive suggestions. I retained full control over all aspects of the thesis, including content development, analysis, language, and final presentation. No sections were included without careful review, modification, and integration into my own academic work.