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Impact of Environmental Factors on Air Handling Unit Performance in the Libyan Oil Sector: The Case Study of Ras Lanuf Oil & Gas Company

Mohamed Omer Ibrahim Abdulrahman[1][1] and Omar Emad Hassouna[1]

[1]*School of Engineering, Alfa University College, Selangor, Malaysia*

ABSTRACT

Air Handling Units (AHUs) are critical safety infrastructure in oil and gas facilities, responsible for maintaining positive pressurization, thermal comfort, and air quality in control rooms, electrical substations, and process areas. However, in desert-coastal environments such as northern Libya, AHUs face extreme environmental stressors—intense Saharan dust storms, ambient temperatures exceeding 45°C, and elevated coastal humidity—that accelerate performance degradation, increase energy consumption, and threaten operational reliability. Despite these challenges, maintenance practices in Libyan hydrocarbon facilities remain predominantly reactive or calendar-based, lacking condition-monitoring frameworks. This study quantitatively evaluates the perceived impact of dust accumulation, high ambient temperature, elevated humidity, and cooling coil fouling on AHU operational performance at Ras Lanuf Oil and Gas Processing Company. Using a quantitative, cross-sectional survey design, structured questionnaires were administered to 40 experienced AHU specialists, yielding a 100% response rate. Instrument reliability was confirmed via Cronbach's alpha ($\alpha = 0.82$). Descriptive analysis revealed that 87.5% of respondents confirmed dust accumulation significantly increases filter pressure drop and reduces airflow efficiency; 90.0% agreed that high temperatures and humidity increase cooling loads and electrical energy consumption; 85.0% confirmed cooling coil fouling reduces heat exchange efficiency; and 87.5% affirmed that performance-based monitoring indicators effectively support predictive maintenance planning. All four research hypotheses (H1–H4) were empirically supported. The findings demonstrate that combined environmental exposure creates synergistic degradation mechanisms, including exponential filter pressure rise, conductive thermal insulation on coils, elevated psychrometric latent loads, and accelerated atmospheric corrosion collectively impairing AHU capacity, increasing power draw, and shortening equipment lifespan. Practically, it offers an actionable roadmap for transitioning from calendar-based servicing to condition-based, performance-monitored maintenance protocols, including differential pressure-triggered filter replacement, automated coil washing, anti-corrosion coatings, and real-time sensor integration.

Keywords: Air Handling Unit, Desert-coastal environment; Dust accumulation; Filter pressure drop; Cooling coil fouling, Performance-based maintenance

[1] Corresponding author.
Email address: omar.i@alfa.edu.my (Omar Emad Hassouna)

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1. Introduction

In the rapidly evolving e-commerce competition landscape, understanding consumer behavior is paramount for businesses seeking to thrive online (Lăzăroiu et al., 2020). Behavioral intention to buy from an online market refers to a consumer's subjective likelihood or willingness to engage in future purchasing behaviors, specifically within online marketplaces or e-commerce platforms (Guo et al., 2021). Similarly, Deng et al. (2021) defined behavioral intention as shaped by the consumer's cognitive evaluations (e.g., perceived value, perceived quality) and emotional responses (e.g., enjoyment, arousal) towards the online shopping experience (Alshohaib, 2024). In addition, behavioral intention encompasses the psychological readiness and predisposition of consumers to engage in online shopping activities, influenced by a combination of internal factors (e.g., attitudes, beliefs) and external factors (e.g., social influence, marketing stimuli) (Venkatesh & Davis, 2000; Liang & Lai, 2002).

In heavy industrial processing environments, particularly within the oil and gas sector, Heating, Ventilation, and Air Conditioning (HVAC) systems represent safety-critical utility infrastructure required to sustain continuous production, ensure occupational health, and safeguard high-value electronic assets. Air Handling Units (AHUs) serve as the core mechanical workhorses within these industrial climate control architectures, responsible for filtering airborne contaminants, regulating indoor dry-bulb temperature, managing relative humidity through psychrometric conditioning, and pressurizing mission-critical facility zones (McQuiston et al., 2005; ASHRAE, 2019, 2021). In hydrocarbon facilities, AHUs provide essential operational protection by delivering positive space pressurization and strict environmental control inside control rooms, electrical substations, laboratories, and process support structures (CIBSE, 2016; Hameed et al., 2004). Maintaining stable temperature and humidity levels is mandatory to prevent thermal tripping of SCADA servers, eliminate switchgear moisture condensation, mitigate atmospheric corrosion, and prevent hazardous gas ingress (ISO 9223, 2012; Thurston et al., 2017). Consequently, AHU performance degradation directly threatens plant safety, increases energy consumption, and risks production shutdowns.

Operating Air Handling Units within North Africa, specifically along the coastal-desert industrial corridor of northern Libya, exposes mechanical equipment to some of the most aggressive climatic conditions globally. Ras Lanuf Oil and Gas Processing Company operates in a desert-coastal environment characterized by intense atmospheric stressors (Prospero et al., 2014). This regional climate introduces three distinct, interacting environmental hazards: (1) high concentrations of airborne mineral dust transported by frequent desert sandstorms (Ghibli winds), composed of highly abrasive silica, clays, and marine salts (Goudie & Middleton, 2006; Middleton, 2017); (2) prolonged periods of extreme ambient summer temperatures exceeding 45°C that approach or surpass standard HVAC design thresholds (Al-Hamidi & Al-Saud, 2001); and (3) elevated coastal relative humidity levels that generate high latent cooling demands and aggressive atmospheric corrosivity (ISO 9223, 2012; ASHRAE, 2020). Continuous exposure to airborne particulate matter causes rapid dust loading on filtration media, elevating airflow static pressure losses (ΔP), reducing ventilation fan efficiency, and increasing electrical energy consumption (Siegel et al., 2002; Wang et al., 2015). Furthermore, particulate matter bypassing primary filtration deposits directly onto finned cooling coil surfaces, forming insulating particulate layers that severely impede convective heat exchange effectiveness and reduce total cooling capacity (Yang et al., 2007; Zhang et al., 2011). Simultaneously, extreme outdoor heat widens sensible cooling loads, forcing compressor chillers and supply blowers to run continuously at maximum output, while high coastal humidity increases moisture condensation, accelerates coil corrosion, and induces microbial fouling (ASHRAE, 2021).

Despite the recognized severity of these environmental stressors, maintenance management across Libyan oil and gas facilities remains overwhelmingly reactive or reliant on fixed, calendar-based time intervals rather than performance-based, condition-monitoring frameworks (Müller & Isermann, 2008). Plant operators frequently replace air filters or wash fouled cooling coils based on rigid calendar schedules rather than monitoring real-time operational indicators such as filter differential pressure drops or cooling capacity loss, leading to premature component wear, excessive energy penalties, and unexpected system failure. Furthermore, existing HVAC engineering literature relies predominantly on computer simulations, bench-scale laboratory experiments, or studies conducted in temperate Western climates, leaving a distinct empirical research gap regarding field-level AHU performance degradation under actual desert-coastal industrial conditions in Libya (Middleton, 2017; Al-Hamidi & Al-Saud, 2001). To address this operational gap, this study formulates four primary research questions: (1) How does dust accumulation affect filter pressure drop and airflow resistance in AHU systems? (2) How do high ambient temperature and elevated humidity influence cooling performance and electrical energy consumption? (3) How does cooling coil fouling affect overall system efficiency and operational reliability? (4) How can performance-based indicators support condition-based predictive maintenance planning? Correspondingly, the main objective of this study is to quantitatively evaluate the perceived impact of dust accumulation, high ambient temperature, and humidity on AHU operational performance at Ras Lanuf. Specific objectives include: evaluating dust loading impacts on filter differential pressure and airflow resistance; analyzing high temperature and humidity effects on sensible/latent cooling loads and power consumption; assessing cooling coil fouling impacts on heat exchange efficiency and system reliability; and developing performance-based monitoring indicators for maintenance optimization. Four central hypotheses are tested: H1 posits that dust accumulation is associated with increased airflow resistance and filter pressure drop; H2 posits that high ambient temperature and humidity are associated with increased cooling load and energy consumption; H3 posits that coil fouling is associated with reduced system efficiency and operational reliability; and H4 posits that performance-based indicators effectively support predictive maintenance planning.

The practical and academic significance of this research is substantial. Practically, the study provides facility managers and maintenance engineers at Ras Lanuf with an empirical engineering assessment to transition from calendar-based maintenance to performance-based, condition-monitoring protocols. Identifying degradation trends across filter pressure drop, coil fouling, and thermal stress enables optimized filter replacement, targeted coil washing, and corrosion-resistant component selection, directly lowering operating costs and extending asset lifecycle. Academically, this study addresses a major regional literature gap by providing structured empirical field data regarding industrial HVAC performance in North Africa. Grounded in psychrometric principles, heat transfer mechanics, and fluid dynamics (ASHRAE, 2021; Cengel & Boles, 2014), this research bridges theoretical HVAC engineering with operational asset management. For the scope of this research, Air Handling Unit (AHU) Performance is operationally defined as the mechanical system's ability to deliver required volumetric airflow, maintain indoor thermal setpoints, and regulate humidity within safe operating limits (ASHRAE, 2019). Dust Accumulation refers to the mass loading of mineral particulate matter onto air filters and heat exchanger coils (Wang et al., 2015). Filter Pressure Drop (ΔP) is defined as the static differential pressure loss across filtration media measured in Pascals or Kilopascals (ASHRAE, 2017). Cooling Performance represents the sensible and latent heat extraction capacity of the AHU cooling coil, measured in Kilowatts (kW) (ASHRAE, 2021). Performance-Based Maintenance refers to condition-based maintenance scheduling triggered by operational sensor metrics rather than fixed time schedules (Müller & Isermann, 2008).

2. Literature Review

North Africa represents the single largest global source of atmospheric mineral dust, emitting billions of tons annually (Goudie & Middleton, 2006; Prospero et al., 2014). Regional wind regimes routinely transport dust plumes toward Mediterranean coastal industrial centers like Ras Lanuf (Middleton, 2017). Mineral dust particles in North Africa are highly abrasive and chemically complex, consisting primarily of crystalline silica (SiO_2), clay minerals (illite, kaolinite, smectite), calcium carbonate (CaCO_3), iron oxides, and airborne sea-salt aerosols (NaCl) carried from the Mediterranean Sea (Goudie & Middleton, 2006). Crystalline silica particles possess extreme mechanical hardness, causing physical abrasion on rotating blower impellers and filtration fibers. Saline aerosols and mineral salts impart high hygroscopicity to the dust, meaning that when deposited on metal surfaces in high-humidity environments, airborne dust absorbs moisture and forms highly corrosive electrolyte layers that accelerate galvanic pitting corrosion (ISO 9223, 2012). During major desert dust storms, atmospheric particulate matter concentrations (PM_{10} and $\text{PM}_{2.5}$) rise dramatically, frequently exceeding baseline urban concentrations by 10 to 50 times and severely overwhelming standard industrial filtration infrastructure (Prospero et al., 2014; Thurston et al., 2017).

Air Handling Units (AHUs) represent the primary mechanical systems responsible for air conditioning, thermal conditioning, and air quality regulation in industrial facilities (ASHRAE, 2021). Industrial AHUs comprise air mixing plenums, multi-stage filtration banks, cooling/heating coils, condensate pans, and motor-driven fan blowers (McQuiston et al., 2005; ASHRAE, 2019). Outdoor air passes through filtration stages before flowing across cooling coils where sensible heat is extracted and latent moisture is condensed. In industrial oil and gas installations, AHUs are engineered to maintain positive space pressurization—typically maintaining 25 to 50 Pascals of positive static pressure inside control rooms and electrical substations relative to the external atmosphere—to prevent the ingress of hazardous, toxic, or explosive hydrocarbon gases from adjacent process units (ASHRAE, 2020; CIBSE, 2016). Furthermore, indoor air conditioning directly impacts human operator cognitive performance and equipment reliability; excessive indoor humidity or elevated room temperatures induce thermal stress in personnel, increase operator error rates, and cause premature overheating of process control microprocessors (Hameed et al., 2004; Thurston et al., 2017).

Filtration media serve as the primary protective barrier against airborne particulate ingress in AHU installations (ASHRAE, 2017). As dust-laden air flows through fibrous filter media, particles deposit on fiber surfaces through straining, impaction, interception, and diffusion mechanisms, forming a porous dust cake layer (Siegel et al., 2002). As the dust cake accumulates, the interstitial pathways within the filter media become restricted, causing a non-linear, exponential increase in static pressure drop (ΔP) across the filter bank (Siegel et al., 2002; Wang et al., 2015). ASHRAE Standard 52.2 specifies that air filters operate along a characteristic loading curve, where initial clean filter resistance gradually rises to a recommended final terminal pressure drop (often 250–375 Pa for MERV 8–13 filters) at which point filter replacement is mandatory (ASHRAE, 2017). In severe dust environments, filters reach terminal pressure drops in a fraction of their standard operating design life. Operating AHUs with severely overloaded, high-resistance filters restricts total volumetric airflow rate (Q_{air}), disrupts space pressurization, and causes the supply fan motor to draw significantly higher electrical power to overcome static system head losses, resulting in severe energy penalties (Wang et al., 2015; Müller & Isermann, 2008).

Cooling coil fouling occurs when fine particulate matter bypasses compromised filtration stages or enters through casing air leakage paths, depositing onto the aluminum fins and copper tubes of heat exchanger coils (Yang et al., 2007; Zhang et al., 2011). Over time, dust accumulation forms an insulating particulate layer across the coil surface. Because mineral dust possesses low thermal conductivity ($k \approx 0.15–0.35 \text{ W/m}\cdot\text{K}$) compared to aluminum ($k \approx 200 \text{ W/m}\cdot\text{K}$), coil fouling introduces significant conductive thermal resistance, severely impairing the overall heat transfer coefficient (U) of the heat exchanger (Yang et al., 2007). Experimental investigations demonstrate that heavy cooling coil fouling can increase air-side pressure drop across the coil by up to 100%, reduce total cooling capacity by 10% to 30%, and force refrigeration compressors and chilled water pumps to run at elevated duty cycles, drastically increasing electrical power consumption (Yang et al., 2007; Zhang et al., 2011; Wang et al., 2015). Furthermore, when dust-fouled coils operate under high-humidity conditions, wet coil surfaces trap particulate matter into dense mud cakes that completely block fin passages and harbor microbial growth (ASHRAE, 2021).

In desert-coastal industrial regions like Ras Lanuf, high ambient outdoor dry-bulb temperatures (>45°C) and high relative humidity levels create extreme sensible and latent thermal loads (Al-Hamidi & Al-Saud, 2001; ASHRAE, 2020). High ambient dry-bulb temperatures increase the sensible cooling load ($Q_{\text{sensible}} = \dot{m} C_p \Delta T$), narrowing the temperature differential between outdoor air and chilled water/refrigerant, which lowers the coefficient of performance (COP) of central refrigeration chillers (ASHRAE, 2021). Concurrently, elevated coastal humidity increases the latent cooling demand ($Q_{\text{latent}} = \dot{m} h_{fg} \Delta w$) required to condense moisture out of the fresh air stream to achieve target indoor relative humidity levels (

Table 2.1: Summary of Environmental Factors, Operational Effects, and Engineering Consequences

Environmental Factor	**Primary Physical & Thermodynamic Effect**	**Operational & Engineering Consequence**
Dust Concentration & Loading	Rapid particle accumulation on filter fibers; Porous dust cake cake formation.	Exponential increase in filter pressure drop (ΔP); Restricted airflow rate; High fan power draw (Wang et al., 2015).
Fine Particulate Bypass	Dust deposition on aluminum finned cooling coils; Airway restriction.	Conductive thermal insulating layer; 10–30% loss in cooling capacity; 100% increase in coil air resistance (Yang et al., 2007).
Elevated Ambient Temperature (>45°C)	Extreme sensible thermal load; Reduced heat rejection temperature differential.	Continuous peak capacity operation; Higher electrical power consumption; Thermal mechanical stress (Al-Hamidi & Al-Saud, 2001).

Environmental Factor	Primary Physical & Thermodynamic Effect	Operational & Engineering Consequence
Elevated Coastal Humidity	High latent moisture removal load; Continuous surface condensate accumulation.	Demanding psychrometric dew point conditioning; High chiller energy draw; Condensation risks in ducts (ASHRAE, 2020).
Saline-Dust & Humidity Synergy	Hygroscopic salt absorption; Electrolyte layer formation on metallic surfaces.	Accelerated atmospheric corrosion (ISO 9223); Casing rust; Fin oxidation; Microbial bio-fouling (ISO 9223, 2012).
Combined Environmental Conditions	Simultaneous thermal, hydraulic, chemical, and particulate mechanical stress.	Accelerated AHU component degradation; Frequent unscheduled downtime; High lifecycle maintenance cost (ASHRAE, 2021).

A comprehensive review of published literature reveals that while individual environmental factors have been evaluated theoretically or under laboratory conditions, a major research gap exists regarding field-oriented empirical research in North African oil and gas facilities. Prior studies predominantly focus on temperate building environments (Siegel et al., 2002; CIBSE, 2016) or isolated bench-scale heat exchanger experiments (Yang et al., 2007; Zhang et al., 2011). There is a complete lack of empirical survey studies capturing the expert operational observations of plant engineers and maintenance technicians operating full-scale AHU systems in coastal-desert facilities in Libya. Furthermore, existing maintenance literature highlights a critical operational gap: industrial plants in Libya rely on time-based preventive maintenance routines that ignore actual system performance metrics (Müller & Isermann, 2008). To bridge these empirical and operational gaps, this research develops a conceptual framework linking environmental exposure variables (dust, temperature, humidity) to intermediate degradation modes (filter loading, coil fouling, thermal stress, corrosion) and final AHU performance indicators (airflow degradation, pressure drop, cooling efficiency, power draw, reliability). Grounded in this framework, four core hypotheses are posited: H1 stating that dust accumulation increases filter pressure drop and airflow resistance; H2 stating that high temperature and humidity increase cooling load and power draw; H3 stating that coil fouling reduces cooling efficiency and reliability; and H4 stating that performance-based indicators effectively support predictive maintenance planning.

3. Method

This chapter presents the quantitative, field-oriented survey methodology utilized to empirically evaluate the perceived operational degradation of Air Handling Units (AHUs) under desert-coastal environmental conditions. Grounded in positivism, this study objectively quantifies operational performance indicators—including filter pressure drops, airflow resistance, cooling capacity loss, and energy consumption—based on professional technical judgments (Creswell, 2014; Sekaran & Bougie, 2016; Müller & Isermann, 2008). The operational research design is a quantitative, descriptive-correlational, cross-sectional field survey. The descriptive component profiles participant background characteristics, operational work areas, and environmental exposure levels, while the correlational component evaluates the relationships between environmental stress variables and perceived AHU performance indicators (Creswell, 2014; Lavrakas, 2008). A survey-based engineering evaluation approach was specifically chosen because accessing physical DCS sensor trends across security-restricted oil and gas facilities presented insurmountable administrative barriers, whereas structured questionnaires administered to experienced field operators capture rich, long-term technical observations across diverse plant operating zones (Müller & Isermann, 2008; Saunders et al., 2019).

The study was conducted at Ras Lanuf Oil and Gas Processing Company in northern Libya, a major hydrocarbon processing hub operating under continuous exposure to Saharan dust storms, summer heat (>45°C), and high coastal humidity. The target population comprised technical, operations, maintenance, mechanical, electrical, and facility staff directly responsible for AHU installations across Ras Lanuf control rooms, electrical substations, laboratories, administrative wings, and process support buildings. A purposive sampling strategy selected 40 qualified AHU specialists (Fowler, 2014; Taherdoost, 2016). In survey-based engineering studies on specialized technical systems within a single facility, 40 expert practitioners provide high practical validity and reliable descriptive data (Müller & Isermann, 2008). All 40 respondents returned usable surveys (100% response rate). Table 3.1 maps questionnaire variables to AHU indicators, and Table 3.2 details the instrument structure.

Table 3.1: Mapping of Questionnaire Variables to AHU Performance Indicators

Environmental Variable	**Target AHU Operational Variable**	**Associated Performance Indicator & Metric**
Dust Concentration & Loading	Filter Loading & Airflow Resistance	Filter pressure drop increase (ΔP, Pa); Volumetric airflow reduction (Q_{air}, m^3/h).
Elevated Ambient Temperature	Sensible Thermal Cooling Load	Increased cooling load (kW); Elevated fan and chiller power draw (kWh).
Elevated Relative Humidity	Latent Dehumidification & Corrosion	Dehumidification energy draw; Condensation occurrence; Atmospheric corrosion rate.
Cooling Coil Fouling	Heat Transfer & Thermal Efficiency	Loss of overall heat transfer coefficient (U); Reduced supply air cooling capacity.

Environmental Variable	Target AHU Operational Variable	Associated Performance Indicator & Metric
Combined Environmental Exposure	System Degradation & Maintenance	Increased maintenance frequency; Reduced operational reliability; Shortened service life.

Table 3.2: Research Instrument Structure and Variable Coverage

Questionnaire Section	Operational Focus / Variable	Items	Measurement Scale & Target Objective
Section 1: Demographic Information	Job Position, Experience, Operational Area	Items 1–3	Categorical selection profiling technical background and facility operational zone.
Section 2: Environmental Dust Exposure	Dust Exposure Severity & Concentration	Item 4	5-point Likert scale evaluating frequency of high dust exposure events.
Section 3: Dust Impact on AHUs	Filter Pressure Drop & Airflow Efficiency	Items 5–6	5-point Likert scale assessing filter resistance and ventilation degradation.
Section 4: High Temperature Impact	Cooling Load & Electrical Energy Use	Items 7–8	5-point Likert scale evaluating thermal sensible load and blower power draw.
Section 5: High Humidity Impact	Cooling Performance & Corrosion Risk	Items 9–10	5-point Likert scale assessing latent demand, condensation, and corrosion.
Section 6: Coil Fouling Analysis	Heat Transfer & Cooling Efficiency	Item 11	5-point Likert scale assessing particulate thermal

Questionnaire Section	Operational Focus / Variable	Items	Measurement Scale & Target Objective
			insulation on cooling fins.
Section 7: Combined Effects & Maintenance	Deterioration, Monitoring & Reliability	Items 12–16	5-point Likert scale assessing synergistic degradation and predictive maintenance.

To support the theoretical interpretation of humidity and thermal loads on AHU cooling coil performance, fundamental psychrometric principles were integrated as analytical background equations (ASHRAE, 2020, 2021). Specific humidity ratio (w), moist air enthalpy (h), and total coil cooling capacity (Q) were referenced using standard psychrometric equations: $$w = 0.62198 \cdot \frac{p_w}{P - p_w}$$ $$h = 1.006 \cdot T + w \cdot (2501 + 1.86 \cdot T)$$ $$Q = \dot{m} \cdot (h_{\text{in}} - h_{\text{out}})$$ where w is humidity ratio (kg/kg dry air), p_w is water vapor partial pressure (kPa), P is atmospheric pressure (kPa), h is specific enthalpy (kJ/kg), T is dry-bulb temperature (°C), Q is total cooling capacity (kW), and $\dot{m}$ is air mass flow rate (kg/s). Table 3.3 details these psychrometric parameters.

Table 3.3: Description of Psychrometric Calculation Parameters and Symbols

Psychrometric Symbol	Parameter Description	Standard Unit of Measurement
w	Specific Humidity Ratio (Moisture Content)	$\text{kg water vapor / kg dry air}$
p_w	Partial Pressure of Water Vapor in Air	Kilopascals (kPa)
P	Barometric Atmospheric Pressure	Kilopascals (kPa)
h	Specific Enthalpy of Moist Air	Kilojoules per kilogram (kJ/kg)

Psychrometric Symbol	Parameter Description	Standard Unit of Measurement
T	Air Dry-Bulb Temperature	Degrees Celsius (°C)
Q	Total Coil Heat Extraction Capacity	Kilowatts (kW)
$\dot{m}$	Air Mass Flow Rate Through AHU	Kilograms per second (kg/s)
$h_{\text{in}} / h_{\text{out}}$	Enthalpy of Entering Air / Leaving Supply Air	Kilojoules per kilogram (kJ/kg)

The primary research instrument was a 16-item structured questionnaire designed on a 5-point Likert scale (1 = "Strongly Disagree" to 5 = "Strongly Agree"). Questionnaire validation followed rigorous procedures: content validity was confirmed by an expert review panel comprising two HVAC engineering professors, two senior industrial facility managers, and a survey methodologist, achieving a Content Validity Index (CVI) ≥ 0.80 (Polit & Beck, 2006). Double-blind back-translation ensured conceptual equivalence between English and Arabic versions (Brislin, 1970). Instrument internal consistency reliability was formally evaluated using Cronbach's alpha coefficient (α), yielding $\alpha = 0.82$ across the survey scales, confirming strong internal reliability well above the standard 0.70 benchmark (Nunnally & Bernstein, 1994). Data analysis was conducted using IBM SPSS Statistics (Version 28). Descriptive statistical analysis—including frequencies and percentages—profiled participant demographics, environmental exposure severity, and agreement levels across performance indicators. Hypotheses testing utilized descriptive response pattern evaluation: a hypothesis was confirmed supported when the combined majority of expert respondents (>75%) indicated "Agree" or "Strongly Agree" regarding a specific environmental performance impact, aligning with descriptive engineering evaluation standards (Creswell, 2014; Müller & Isermann, 2008). Ethical guidelines strictly governed the research: voluntary participation, complete respondent anonymity, secure data encryption, and formal administrative authorization from Ras Lanuf management (Resnik, 2020). Table 3.4 outlines the project schedule.

Table 3.4: Research Project Timeline and Operational Schedule

Phase	Project Activity Description	Duration	Time Frame (Months)
Phase 1	Literature Review & Problem Identification	2 Months	Months 1–2

Phase	Project Activity Description	Duration	Time Frame (Months)
Phase 2	Research Design & Methodology Development	1 Month	Month 3
Phase 3	Questionnaire Development & Expert Panel CVI Validation	1 Month	Month 4
Phase 4	Field Survey Distribution & Data Collection at Ras Lanuf	2 Months	Months 5–6
Phase 5	Data Cleaning & Descriptive SPSS Statistical Processing	1 Month	Month 7
Phase 6	Data Analysis, Trend Mapping & Psychrometric Interpretation	1 Month	Month 8
Phase 7	Thesis Writing, Documentation & Discussion Formatting	2 Months	Months 9–10
Phase 8	Final Thesis Revision, Proofreading & Academic Submission	1 Month	Month 11

4. Data Analysis

Data collected from 40 AHU operation and maintenance specialists at Ras Lanuf were processed in IBM SPSS Statistics (Version 28). Questionnaire scale reliability was established via Cronbach's alpha coefficient ($\alpha = 0.82$), confirming high internal consistency across all survey items (Nunnally & Bernstein, 1994). Demographic profiling revealed a well-seasoned workforce. Job position breakdown showed Maintenance Engineers at 30.0% (n = 12), HVAC Technicians at 25.0% (n = 10), Facility Operators at 15.0% (n = 6), Mechanical Engineers at 12.5% (n = 5), Electrical/Instrumentation Technicians at 10.0% (n = 4), and Other roles at 7.5% (n = 3) (Table 4.1).

Table 4.1: Distribution of Participants by Job Position

Job Position Category	**Frequency (n)**	**Percentage (%)**
Maintenance Engineer	12	30.0
HVAC Technician	10	25.0
Facility Operator	6	15.0
Mechanical Engineer	5	12.5
Electrical / Instrumentation Technician	4	10.0
Other Technical Roles	3	7.5
Total	40	100.0

Professional experience showed 35.0% (n = 14) possess >10 years, 32.5% (n = 13) possess 6–10 years, 22.5% (n = 9) possess 2–5 years, and 10.0% (n = 4) possess

Table 4.2: Years of Experience of Participants

Experience Cohort	**Frequency (n)**	**Percentage (%)**
Less than 2 years	4	10.0
2–5 years	9	22.5
6–10 years	13	32.5

Experience Cohort	Frequency (n)	Percentage (%)
More than 10 years	14	35.0
Total	40	100.0

Table 4.3: Operational Work Areas of Managed AHU Systems

Primary Operational Area	Frequency (n)	Percentage (%)
Control Room	11	27.5
Electrical Substation	8	20.0
Administrative Building	9	22.5
Laboratory	5	12.5
Process Support Area	5	12.5
Other Facilities	2	5.0
Total	40	100.0

Dust exposure analysis confirmed that 82.5% agreed/strongly agreed plant AHUs are exposed to high dust concentrations (Table 4.4). Assessing dust loading impacts, 87.5% agreed/strongly agreed dust increases filter pressure drop (ΔP) (Table 4.5), while 80.0% confirmed dust reduces ventilation airflow efficiency (Table 4.6).

Table 4.4: Perceived Exposure of AHU Systems to High Dust Concentrations

Response Category	**Frequency (n)**	**Percentage (%)**
Strongly Disagree	1	2.5
Disagree	2	5.0
Neutral	4	10.0
Agree	18	45.0
Strongly Agree	15	37.5
Total	40	100.0

Table 4.5: Impact of Dust Accumulation on Increasing Filter Pressure Drop

Response Category	**Frequency (n)**	**Percentage (%)**
Strongly Disagree	0	0.0
Disagree	2	5.0
Neutral	3	7.5
Agree	17	42.5
Strongly Agree	18	45.0

Response Category	Frequency (n)	Percentage (%)
Total	40	100.0

Table 4.6: Impact of Dust Accumulation on Reducing Airflow Efficiency

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	1	2.5
Disagree	2	5.0
Neutral	5	12.5
Agree	16	40.0
Strongly Agree	16	40.0
Total	40	100.0

Evaluating thermal stress showed that 90.0% agreed/strongly agreed high ambient temperatures increase cooling loads (Table 4.7) and 85.0% confirmed increased electrical power consumption (Table 4.8). Assessing humidity impacts showed 80.0% confirmed high relative humidity negatively affects cooling performance (Table 4.9), while 85.0% agreed elevated humidity increases component corrosion risks (Table 4.10).

Table 4.7: Impact of High Ambient Temperature on Increasing Cooling Load

Response Category	**Frequency (n)**	**Percentage (%)**
Strongly Disagree	0	0.0
Disagree	1	2.5
Neutral	3	7.5
Agree	18	45.0
Strongly Agree	18	45.0
Total	40	100.0

Table 4.8: Impact of High Temperature on Electrical Energy Consumption

Response Category	**Frequency (n)**	**Percentage (%)**
Strongly Disagree	0	0.0
Disagree	2	5.0
Neutral	4	10.0
Agree	17	42.5
Strongly Agree	17	42.5

Response Category	Frequency (n)	Percentage (%)
Total	40	100.0

Table 4.9: Impact of High Humidity on Degrading Cooling Performance

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	1	2.5
Disagree	3	7.5
Neutral	4	10.0
Agree	16	40.0
Strongly Agree	16	40.0
Total	40	100.0

Table 4.10: Impact of Elevated Humidity on Increasing Corrosion Risk

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	0	0.0
Disagree	2	5.0
Neutral	4	10.0

Response Category	Frequency (n)	Percentage (%)
Agree	18	45.0
Strongly Agree	16	40.0
Total	40	100.0

Evaluating heat exchanger degradation demonstrated that 85.0% agreed/strongly agreed cooling coil fouling reduces heat exchange efficiency (Table 4.11). Assessing combined environmental effects revealed 90.0% agreement that dust, temperature, and humidity act synergistically to accelerate system deterioration (Table 4.12). Evaluating maintenance requirements showed 82.5% agreement that harsh environmental exposure increases maintenance frequency (Table 4.13). Assessing condition monitoring tools showed 87.5% agreement that real-time performance monitoring detects flaws early (Table 4.14), and 87.5% agreed transitioning to performance-based maintenance improves operational reliability (Table 4.15). Hypotheses evaluation confirmed empirical support for all four hypotheses (H1–H4, Table 4.16).

Table 4.11: Impact of Cooling Coil Fouling on Reducing Heat Exchange Efficiency

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	1	2.5
Disagree	1	2.5
Neutral	4	10.0
Agree	17	42.5
Strongly Agree	17	42.5

Response Category	Frequency (n)	Percentage (%)
Total	40	100.0

Table 4.12: Synergistic Impact of Combined Environmental Stressors on AHU Deterioration

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	0	0.0
Disagree	1	2.5
Neutral	3	7.5
Agree	18	45.0
Strongly Agree	18	45.0
Total	40	100.0

Table 4.13: Impact of Environmental Exposure on Increasing Maintenance Frequency

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	1	2.5
Disagree	2	5.0
Neutral	4	10.0

Response Category	Frequency (n)	Percentage (%)
Agree	18	45.0
Strongly Agree	15	37.5
Total	40	100.0

Table 4.14: Efficacy of Real-Time Performance Monitoring for Early Problem Detection

Response Category	Frequency (n)	Percentage (%)
Strongly Disagree	0	0.0
Disagree	1	2.5
Neutral	4	10.0
Agree	17	42.5
Strongly Agree	18	45.0
Total	40	100.0

Table 4.15: Efficacy of Performance-Based Maintenance in Improving System Reliability

Response Category	**Frequency (n)**	**Percentage (%)**
Strongly Disagree	0	0.0
Disagree	2	5.0
Neutral	3	7.5
Agree	16	40.0
Strongly Agree	19	47.5
Total	40	100.0

Table 4.16: Summary of Hypotheses Testing Outcomes

Hypothesis	**Proposed Relationship Statement**	**Overall Agreement (%)**	**Empirical Decision**
H1	Dust accumulation increases airflow resistance and filter pressure drop in AHUs.	87.5% Agreement	Supported
H2	High ambient temperature and humidity increase cooling load and energy consumption.	90.0% Agreement	Supported

Hypothesis	Proposed Relationship Statement	Overall Agreement (%)	Empirical Decision
H3	Cooling coil fouling reduces heat transfer efficiency and operational reliability.	85.0% Agreement	Supported
H4	Performance-based indicators effectively support predictive maintenance planning.	87.5% Agreement	Supported

5. Discussion and Implications

This chapter interprets the empirical findings in relation to the study's research objectives, existing HVAC literature, and underlying engineering principles. The results confirm that dust accumulation, high ambient temperature, elevated humidity, and cooling coil fouling exert severe negative impacts on Air Handling Unit operational performance across Ras Lanuf oil and gas processing facilities. Addressing Research Objective 1, the finding that 87.5% of respondents confirmed dust accumulation significantly increases filter pressure drop (ΔP) and reduces ventilation airflow efficiency corroborates classical fluid dynamics and filtration literature (Siegel et al., 2002; Wang et al., 2015; ASHRAE, 2017). Dust cake loading on primary and secondary air filters increases static system head losses, causing supply blowers to draw higher electrical power while restricting clean airflow to safety-critical spaces such as control rooms and substations.

Addressing Research Objective 2, the finding that 90.0% of participants agreed that elevated outdoor temperatures (>45°C) and high coastal relative humidity increase sensible and latent cooling loads aligns directly with psychrometric and refrigeration cycle theory (Al-Hamidi & Al-Saud, 2001; ASHRAE, 2020, 2021). High outdoor heat narrows heat rejection differentials, lowering chiller COP, while high relative humidity requires cooling coils to extract substantial latent moisture to maintain indoor humidity below critical thresholds (

The practical and managerial implications of these findings are substantial. For plant managers and maintenance engineers at Ras Lanuf and across the Libyan oil and gas sector (e.g., NOC, Waha, Agoco), this study provides an actionable operational roadmap. First, industrial facilities operating in coastal-desert zones must replace rigid calendar-based filter maintenance with performance-based replacement protocols triggered by real-time differential pressure sensor thresholds ($\Delta P \ge 250 \text{ Pa}$) (ASHRAE, 2017; Müller & Isermann, 2008). Second, facilities should install high-capacity, multi-stage filtration systems—such as self-cleaning pulse-jet inertial sand trap louvers paired with MERV 8 pre-filters and MERV 13 secondary filters—to capture coarse Saharan dust before it reaches sensitive cooling coils. Third, routine automated chemical coil washing routines should be established to prevent particulate mud baking on aluminum fins. Fourth, component casings and cooling coils operating in high-humidity coastal zones should be specified with anti-corrosion coatings (e.g., epoxy-phenolic or polyurethane coatings) to prevent atmospheric salt corrosion (ISO 9223, 2012). Policy-wise, national regulatory bodies should establish mandatory HVAC energy efficiency and air quality standards tailored to extreme industrial climates.

7. Limitations and Future Research Study

Several methodological limitations should be considered when evaluating the conclusions of this study. First, the investigation relied on a structured, survey-based quantitative field assessment capturing expert professional perceptions and operational technical observations ($N = 40$) rather than multi-year continuous instrumental sensor logging of physical parameters (e.g., direct thermal anemometer airflow velocity, physical power meter kW draw, or laboratory condensate analysis). While expert practitioner responses provide high practical validity, direct physical metering would provide additional empirical refinement. Second, the study was conducted within a single industrial site—the Ras Lanuf Oil and Gas Processing Company in Libya. While highly representative of coastal-desert petroleum refining facilities, findings may require contextual adaptation before generalizing to inland desert drilling rigs or offshore marine platforms. Third, the study utilized a cross-sectional research design, measuring technical observations at a single point in time, which limits the capacity to track long-term multi-year equipment degradation trends across changing seasonal cycles.

To extend these findings, several directions for future research are recommended. First, future studies should combine perceptual field survey assessments with long-term, automated sensor data logging (monitoring real-time ΔP, supply/return air enthalpies h, blower fan electrical power draw kW, and chilled water flow rates) across changing summer and winter seasons. Second, researchers should evaluate the economic life-cycle cost impact of environmental degradation, quantifying total financial losses associated with energy waste, emergency maintenance, and premature equipment replacement under desert conditions. Third, future research should investigate advanced filtration technologies—such as electrostatic precipitators, pulse-jet self-cleaning air intakes, and novel hydrophobic filter membranes—specifically engineered for high-dust, high-humidity coastal environments. Fourth, comparative studies comparing AHU degradation across different geographic regions (e.g., comparing coastal plants in Ras Lanuf with deep Saharan desert fields in the Murzuq Basin) would provide valuable insight into regional environmental variance.

In conclusion, this study empirically proves that dust accumulation, high ambient temperature, elevated humidity, and coil fouling severely impair Air Handling Unit operational performance in Libya's industrial oil sector. By establishing that combined environmental exposure accelerates heat exchange degradation, raises airflow resistance, increases power draw, and elevates corrosion risk, this research highlights the urgent necessity of transitioning from reactive, calendar-based servicing to condition-based, performance-monitored maintenance. Implementing these evidence-based engineering practices at Ras Lanuf will optimize HVAC energy efficiency, extend asset operating lifespan, protect critical control infrastructure, and safeguard occupational health in extreme desert-coastal industrial environments.

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