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Mitigating Emissions and Improving Vapor Recovery Efficiency: A Comprehensive Analysis of Vapor Recovery Systems in Crude Oil Loading Operations

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ABSTRACT

This review investigates the role and efficiency of Vapour Recovery Systems (VRS) implementation during crude oil loading operations, evaluating their influences on volatile organic compound emissions reduction, mitigating occupational health risks, enhancing environmental sustainability and economic benefits. This research indicates that VRS reduces VOC emissions by up to 95%, effectively mitigating air pollution and noticeably decreasing environmental pollution. Mitigated hydrocarbon exposure through VRS due to VRS installation significantly contributed to a decline in symptoms such as dizziness, headaches, and respiratory distress. From a financial standpoint, mitigating VOC emissions and maintaining regulatory standards yielded notable economic profits. Developed technology adoption like DCS, timely monitoring and analytical maintenance, enhances operational efficiency, recovery rates and minimising downtime effectively. This study underscores the comprehensive integrative value of VRS in revealing its capability to simultaneously advance operational efficiency, ecological sustainability, occupational health safety, and cost-effectiveness across petroleum operations.

Keywords: Volatile Organic Compounds (VOCs), Vapor Recovery Unit (VRU), Environmental And Occupational Impact, Emissions Assessment; Air Quality, Regulatory Compliance, Technological Advancements, Real-time Monitoring, Vapor Recovery System (VRS), Crude Oil Loading.

1 INTRODUCTION

The release of vapours during crude oil loading has become a significant challenge in large-scale petroleum transportation, particularly during tanker truck filling operations. Vapour losses not only pose environmental and occupational health risks but also result in notable economic inefficiencies. During these operations, volatile organic compounds (VOCs) are emitted into the atmosphere, contributing to air pollution, smog formation, and ozone accumulation at ground level. These emissions contain harmful hydrocarbons, including methane, which has a global warming potential far exceeding that of carbon dioxide [1–3]. Without sufficient vapour recovery measures, valuable hydrocarbons are wasted, resulting in financial losses and noncompliance with environmental regulations. Over the past decades, increased awareness of the environmental and health consequences of such emissions has led to the development and implementation of vapour recovery systems (VRS). These technologies aim to capture and repurpose vapours from crude oil during transfer operations, thereby reducing emissions and improving operational efficiency [4]. Historically, emissions during oil loading were largely unregulated, especially in industrial zones of the mid-20th century, where deteriorating air quality became a widespread concern [5]. As shown by recent data from Transneft Company, the trend in loading and transhipment volumes of petroleum products continues to rise, further amplifying the need for effective emission control strategies [6]. Vapour recovery units (VRUs), which are designed to capture up to 95% of vapour emissions [7], have become a vital investment in crude oil logistics. These systems not only mitigate atmospheric pollution but also offer economic benefits through the recovery and potential reuse or commercialisation of captured hydrocarbons [8]. From a safety perspective, vapour accumulation increases the risk of fires and explosions, particularly in confined spaces such as tanker compartments and storage facilities. Chronic exposure to emissions has also been linked to respiratory diseases, neurological disorders, and other long-term health issues [9-14]. Addressing these risks requires integrated technological solutions, such as advanced VRUs that enhance vapour capture

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while maintaining safe and reliable operation through intelligent control systems [11]. This paper presents a comprehensive review of vapour recovery systems used in crude oil loading operations, with a focus on emission mitigation, safety improvements, and operational efficiency. The review consolidates findings from recent studies (2020–2024) and evaluates the technological advances in vapour recovery processes, particularly the performance of VRUs under varying field conditions. Despite ongoing improvements, there remains a clear scientific gap regarding the optimisation of VRU performance for different operational environments, especially in developing regions where infrastructure limitations and regulatory enforcement vary. In addition, there is limited consolidated analysis of both the environmental and economic trade-offs of large-scale vapour recovery deployment. The objective of this review is to critically assess the effectiveness of vapour recovery systems in reducing emissions during crude oil loading, identify knowledge gaps in current applications, and recommend pathways for optimising system performance and enhancing compliance with environmental standards.

2 LITERATURE REVIEW

2.1 A HISTORICAL PERSPECTIVE AND CONTROLLING STRATEGIES: CAPTURING GAS VAPORS DURING CRUDE OIL LOADING OPERATIONS INTO TANKER TRUCKS

Crude oil transportation, in particular during loading operations into oil tanker trucks, has long been identified as a major source of VOCs emissions and other gaseous pollutants. Vapour emissions containing hydrocarbons present substantial risks to both environmental quality and health. The gas emissions history associated with crude oil loading operations has evolved expressively due to growing environmental concerns, safety protocols, and the development of governing contexts to address these challenges [15]. This study presents an in-depth analysis of the historical development of gas emissions associated with loading activities, with specific emphasis on the adoption of vapour recovery technologies and regulatory standards for emissions reduction in the petroleum industry. In the initial years of crude oil loading operations, emissions were not regulated and large amounts of volatile organic compounds, including toluene, methane and benzene and other VOCs, were emitted into the air [16]. This unregulated emission has expressively declined air quality in areas around industrial regions, leading to the formation of smog and other environmental concerns [17]. Through the early growth of the oil industry, mainly in the mid-20th century, environmental concerns were moderately limited. The international requirement of oil and regional transportation caused the establishment of loading terminals where oil was transferred into tanker trucks [18]. These preliminary loading operations were often fundamental, with minimal care for safety procedures. During the early oil industry, the focus on throughput was generally at the detriment of environmental control, to which high emissions of VOCs ensued [19]. The consequences of inadequate emission control, such as hydrocarbon emissions released during crude oil loading activities, became more evident. This period marked a change in public sentiment toward air pollution, as rising awareness of the destructive effects of air pollution on both health and the environment drove growing concern. Emerging scientific research emphasised the unfavourable influences of airborne pollutants, causing governments to pledge advanced policies designed to reduce air pollution [20]. As per reports, a significant turning point occurred with the Clean Air Act of 1970, which took oil and gas activities under the same environmental protocols as other industries [21]. It authorised the EPA to take primary responsibility to control air emissions from these operations, expressly advancing air pollution regulation [20]. The 1990 adjustments to the Clean Air Act marked a key shift in the management of air quality, mainly concerning volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). These deviations presented firmer vapour emission limits for industrial operations, as well as crude oil transfer, with the EPA aiming to subsidise petroleum operations that subsidized to reduce smog in industrial areas [22]. Additionally, the amendments defined the VOC vapour emissions limit for loading operations, prompting the adoption of (VRUs) to capture and condense vapour emissions during loading activities, leading them to be reutilised, thereby mitigating harmful vapour emissions [23]. Hence, this policy shift in early policies created a standards framework surrounding underpins the current widespread use of VRSs, but there is still a significant lack of global implementation, particularly across developing countries. Even with the improvement in the regulations, the limited incorporation of VRS in the developing areas, based on economic and infrastructure limitations, necessitates further research.

2.2 OVERVIEW OF VAPOUR RECOVERY AND TECHNOLOGICAL DEVELOPMENTS

2.2.1 TECHNOLOGICAL PROGRESS AND VAPOUR RECOVERY UNITS' ADOPTION

Vapour recovery units were widely installed at crude oil loading terminals across the U.S by the mid-1990s, propelled by stricter strategies aiming to reduce emissions of VOC. Primary VRU systems were moderately unproductive, but technological improvements soon facilitated more operative and cost-effective designs. The Stage I systems were introduced in the 1990s, capturing vapour emissions during the initial loading phase, while in the early 2000s, Stage II was introduced to address vapour emissions from later filling stages [24]. According to Craig [25] The air quality issues in areas like California and the EU prompted even severe local protocols. California's Air Resources Board (CARB), for example, directed near-total VOC capture during loading and unloading, advancing global adoption of vapour recovery systems. Continuous technological advancement and changes in operational follows have knowingly altered vapour recovery in the industry. Nowadays, firmer environmental protocols, combined with developments in recovery technology, have led to the extensive implementation of more effective vapour recovery systems. Contemporary systems, such as dual-phase recovery units and vacuum-assisted technologies, are accomplished of catching a larger volume of vapours during loading activities by instantaneously dealing with both vapour and liquid phases. These enhancements lead to a considerable decrease in emissions [26]. Vapour recovery systems not only provide environmental advantages but also improve operational safety. By controlling the accumulation of hazardous vapours at loading stations, these systems reduce the risks of explosions and fires. Therefore, many transportation facilities and refineries progressively focus on advanced vapour recovery technologies to conform to strict emission ideals, advance operational effectiveness, and address safety and environmental issues more efficiently. The issue of air pollution has emerged as a worldwide issue, causing many countries to implement regulations to control emissions, particularly from oil and gas operations. In the EU, the VOCs solvents directive (1999/13/EC) establishes limits on volatile organic compound emissions during loading operations [27]. Out there in Europe, countries like Canada, Japan, and Australia have also applied strict vapour emission protocols, illustrating practices from the U.S. and Europe while acclimatising them to local environmental and industrial settings. For instance, Canada's National Air Pollution Investigation Program and Japan's Air Pollution law controller dictate the utilize of vapour recovery systems during oil loading, reflecting a broader global effort to encourage cleaner industrial applications products [28]. The historic course of vapour emissions during crude oil loading operations mirrors the rising acknowledgement of environmental and occupational health risks related to VOC emissions. The oil and gas industry has underscored significant steps in lessening the environmental impact of these activities, starting from initial unregulated practices to the introduction of firm regulatory contexts and technological solutions such as VRUs. VRSs are an essential part of oil filing operations worldwide nowadays, ensuring significant compliance with atmosphere protocols, advancing safety and decreasing environmental risks. Although VRU technologies have developed appreciably since the 1990s, the adoption of effective technologies for emissions reduction is not uniform across different regions, primarily because of cost, regulation absence and infrastructure constraints.

2.2.2 TECHNOLOGIES AND METHODS IN VAPOUR RECOVERY

2.2.2.1 ACTIVE VAPOUR RECOVERY SYSTEMS

Active vapour recovery systems typically involve the combination of compression, condensation, absorption, and adsorption to catch vapours, regularly achieving up to 90% effectiveness. For example, these systems use a combination of absorption and condensation to capture VOCs, which are then separated and recovered. Active systems focus on multipart machinery that aggressively extracts vapours from storage or transport systems [29]. These systems can attain high recovery rates, often above 90% in measured environments. High-throughput loading racks in refineries and marine terminals, where significant amounts of crude oil are moved daily, are frequently equipped with active vapour recovery systems. To collect displaced vapours, compress them, and then either channel them back to the liquid phase or treat them for reuse, VRUs are incorporated into loading arms and storage tanks in these types of facilities. In addition to extracting hydrocarbons that are economically useful, this guarantees adherence to stringent environmental requirements. This makes the system supreme for high-emission scenarios such as crude oil loading [30]. Active systems require significant energy, causing increased operational costs and environmental impact due to high energy consumption. Implementing active vapour recovery systems through crude oil loading operations provides key benefits, including mitigated vapour emissions, enhanced safety, and enhanced cost effectiveness. These systems can capture up to 90% of VOCs, reclaiming valuable hydrocarbons and expressively cutting environmental impact, declining vapour emissions by over 330 tons per (VLCC) Very Large Crude Oil Carrier [31]. As revealed by a North Dakota research, Merhane Kamel [2] Active vapour recovery systems are proficient in 55% mitigation of low-pressure flaring by continually determining and governing oil vapour pressure, eventually reducing both flaring and vapour emissions. Recovering volatile organic compounds means more of the oil is sold instead of flaring. The systems can avoid expensive vapour recovery towers and mitigate costs associated with vapour recovery compression [32]. Active vapour recovery systems can mitigate the explosion and fire hazard by capturing vapours before the discharge into the atmosphere [33]. The technology is desirable to help reduce air pollution and lead to advanced workplace safety during oil loading activities. Although initial investment and maintenance costs may deter small operators, the long-term savings and environmental regulation compliance typically outweigh the issues; a schematic of the tank gas emission control system is shown in Figure 1.

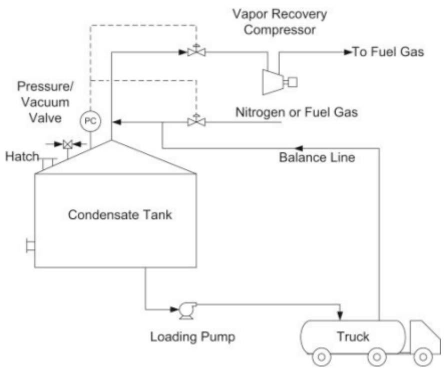

FIGURE 1. Schematic of the tank emission control system [34]

Figure 2 shows the superior effectiveness of active vapour recovery systems compared to other vapour control technologies.

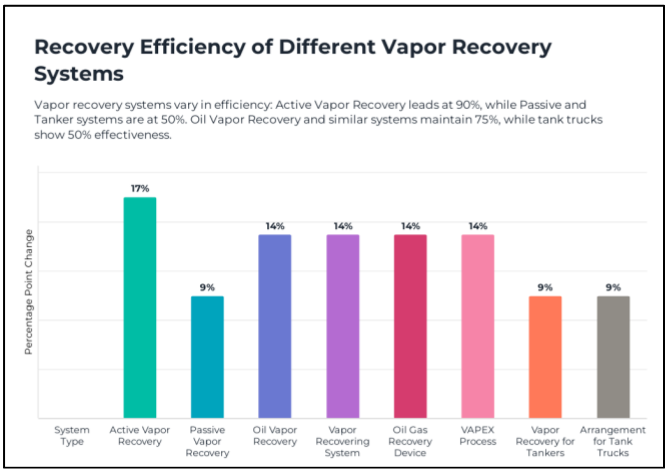

FIGURE 2. Compared the recovery efficiency of some different systems

2.2.2.2 PASSIVE SYSTEMS FOR CAPTURING VAPOURS

These non-mechanical vapour recovery systems operate based on vapour-balanced loading and unloading operations, where vapours act as blanket gases for allowing storage vessels to be stabilised. Passive systems are typically easier in design but offer less efficiency compared to active systems [36]. Still, these systems can be operative in circumstances where there's only a small amount of vapour. The essential difference between passive and active vapour recovery devices lies in their operational mechanisms and total efficiency in mitigating vapour emissions. Active vapour recovery systems typically utilise mechanically driven processes that require an external energy source, while passive systems focus on natural processes and work without external energy. The non-active systems typically implement the vapour balanced loading method, in which vapours displaced loading are transmitted as a blanket gas to enable recovery without mechanical contribution [37]. Although passive systems commonly accomplish lower recovery proficiencies compared to active systems, they can still provide meaningful gas emission mitigations, mainly in low-gas emission or smaller-scale applications. Passive vapour recovery systems generally offer a more cost-efficient solution due to lower energy consumption and minimal operational expenses, making them suitable for smaller-scale activities or settings with limited gas emissions. In contrast, active systems, though expressively more effective in capturing vapours, involve higher installation, maintenance costs and energy. While passive systems are considerably less effective in managing high-emission volumes, they characterise a practical and workable substitute for operations targeting to decrease environmental influence without sustaining considerable operational costs.

2.2.2.3 VAPOUR RECOVERY ARRANGEMENTS IN TANK TRUCKS

Each tank partition is associated with a common vapour recovery pipe, which proficiently conduits VOCs to a designated recovery system. This system avoids unrestrained gas emissions and confirms amenability with environmental protocols [38]. To avoid fire hazards to constrain flame propagation, detonation arrestors are installed at key intersections. In addition, slow-burning ventilators will control the release of vapour emissions, mitigating the combustion risk in enclosed areas. By recovering volatile organic compounds, these systems can mitigate atmospheric pollution as well as improve fuel efficiency. Regulatory figures such as the U.S. Environmental Protection Agency (EPA) require the implementation of such recovery systems in the transport of hazardous material [39]. The advanced approach reveals how integrating conduits and ventilators is improving tanker truck design. Safety and operational performance are advanced through these measures, which help meet global emission standards. Figure 3 shows how state 1A recovery equipment is installed. Table 1 presents a comparison of some vapour recovery systems,

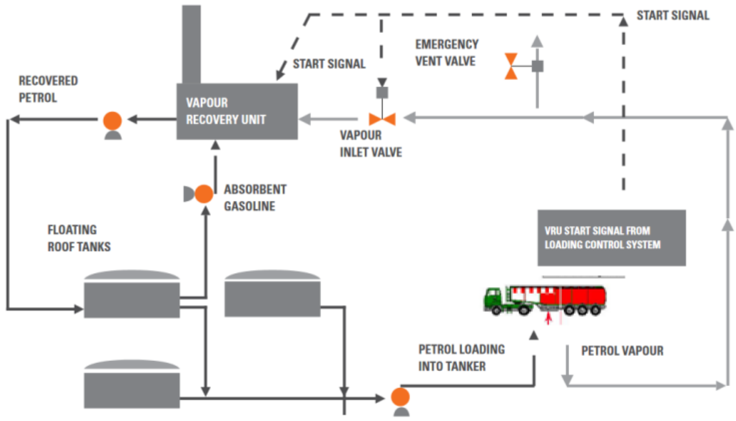

FIGURE 3. Typical system layout of Stage 1A vapour recovery components [40]

Table 1. The comparison of some Vapour Recovery Systems

Type of System	Working Principles	Recovery Efficiency	References
Active Vapour Recovery	Utilises compression, condensation, absorption, and adsorption	High- High	[41]
Vapour Recovery System	Employs absorption columns, distillation, and condensation	High- High	[39]
Oil Vapour Recovery	Cools and condenses oil vapours to regenerate liquid oil	High	[42]
Vapour Recovering System	Incorporates adsorption tanks and a separator	High	[43]
VAPEX Process	Uses solvent injection to recover heavy oil	High	[44]
Oil Gas Recovery Device	Absorption and condensation mechanisms	High	[45]
Tank Trucks Arrangement	Connect detonation and slow-burning ventilators connected to a shared vapour collection pipe.	Moderate	[46]
Passive Vapour Recovery	Relies on vapour-balanced loading/unloading	Moderate	[2]
Tankers Vapour Recovery	Features lockable connections for vapour displacement and recovery pipes	Moderate	[45]

2.3 VAPOUR RECOVERY CONTROL SYSTEM

2.3.1 LOADING VRU CONTROL SYSTEM

The Loading Vapour Recovery Unit control system is crucial for improving the vapour recovery process during oil filling activities. By integrating progressive control strategies, the system guarantees supreme vapour recovery effectiveness while keeping safe and dependable operations. Process system analysis plays a key role in enhancing VRU performance. Using software simulation programs like Aspen HYSYS, engineers can model the complete crude oil processing unit to recognise serious issues upsetting vapour recovery, such as temperature, pressure, and vapour-liquid ratio [47]. This study allows the design of well-organised VRUs that optimise recovery while reducing energy consumption. Loading VRU control system associations, operating system analysis, vapour-liquid ratio control, and progressive distribution control; systems, technology to confirm high-effectiveness vapour recovery, mitigated energy consumption, and enhanced operations performance. This integrated method is vital for accomplishing both ecological and financial profits during crude oil loading activities [48].

2.3.2 PROCESS SYSTEM ANALYSIS AND OPTIMISATION

Analysis system of recovery process are crucial for improving vapor recovery, researchers can investigate critical factors such as pressure, temperature, and liquid content that influence vapor recovery trough utilizing tools to simulate entire crude oil processing unit, These simulations support in designing more effectual (VRUs) that maximize liquid recovery while decreasing energy consumption. Vapour Recovery Units mitigate volatile organic compound emissions while proceeding crude oil loading operations, improving environmental strategy, sustainability and effectiveness. Increasing the performance of VRU involves analysing process systems, emission control and energy consumption. Tools such as simulation Aspen HYSYS assist in identifying upsetting vapour recovery, such as temperature and pressure VRU design improvement. Such systems utilise condensation, compression, adsorption, and absorption to process and recover hydrocarbons, reaching over 90% effectiveness in controlled situations [47]. Nevertheless, these systems require substantial energy, increasing operational costs and environmental impact [49]. The strategy of processing optimisation involves real-time monitoring, energy recovery methods like heat exchangers, as well as automation. Using effective compressors and developed adsorption materials, this approach boosts the system's performance. Through advanced vapour-liquid separation, VOC emissions reduction, renewable energy sources integration, and stabilised maintenance will be achieved.

2.3.3 RATIO CONTROL OF VAPOUR-LIQUID

The ratio of vapour to liquid is crucial to improve vapour recovery system efficiency, since it directly influences recovery performance. A study by [32] Illustrate that at temperatures between 0°C and 20°C, a ratio of 1.0 is sufficient, while at temperatures above 30°C, a ratio of 1.3 advances both energy efficiency and recovery. Temperature affects the volatility of hydrocarbons and the vapour-liquid balance, upsetting it. Systems can enhance the adsorption and condensation performance and reduce energy consumption by regulating the ratio, which is effective for continual recovery during storing and loading operations [50]. Distributed Control Systems have enhanced oil loading and vapour recovery supervision by participating in process control at numerous levels. Utilising PLCs and multi-display systems, DCS allows real-time monitoring, improving reliability and effectiveness [51]. In vapour recovery, Distributed Control Systems provide precise control over critical parameters like pressure, temperature, and flow rates, enhancing recovery performance and mitigating energy usage. It also allows for facilitating maintenance and troubleshooting, enhancing the general efficiency of the system. By faultlessly integrating control levels, Distributed Control Systems certifies flexibility and receptiveness, vital for improving crude oil loading and vapour recovery. [52-53]. Table 2 illustrates a Comparison of Key Aspects of vapour recovery Systems.

Table 2. Comparison of Key Aspects of Vapour Recovery Systems

Method	Key Features	References
Emissions Reduction and Estimation	Utilise mathematical models and experimental methods to assess and mitigate vapour emissions.	[48]
DCS	Integrate process management and control systems for enhanced reliability	[54]
Loading Processes Optimisation	Advances in algorithms to improve oil loading operations from terminals to tankers	[55]
Analysis of Process System	Crude oil processing simulation units to enhance the efficiency of vapour recovery	[56]
Vapour-Liquid Ratio Control	Modification of the vapour-liquid ratio based on temperature for optimum recovery	[57]
Controlled Systems of Frequency Conversion	Automatic regulation of the vapour-liquid ratio utilising flow meters and sensors	[58]

2.3.4 ENVIRONMENTAL AND OCCUPATIONAL HEALTH IMPACTS OF HYDROCARBON VAPOR EMISSIONS

The VOC emissions, during the oil filling operation, have had significant environmental and health effects. The vapour released commonly linked with the handling and transfer of petroleum products, assist significantly contributes to atmospheric pollution, climate change, and degradation of surrounding ecosystems. Volatile organic compounds are key contributors to ground-level ozone, a principal component of smog that harms and threatens health and the environment. Furthermore, many hydrocarbons work like powerful greenhouse gases, contributing to climate change. The continuous release of these pollutants also contributes to the degradation of ecosystems by polluting water and soil sources, eventually unsettling biodiversity and spoiling plant and animal life [59]. Vapour recovery systems are crucial for hydrocarbon emissions mitigation, significantly decreasing vapour release, improving air quality, and restraining greenhouse gases [60]. Vapour recovery adoption technologies contribute to environmental regulations compliance, also protecting public health [61]. Beyond environmental concerns, the hydrocarbon vapours released during oil loading activities offer massive occupational health risks. Continued exposure to these vapours leads to respiratory troubles, which include neurological effects such as headaches and dizziness and COPD and asthma. Workers near oil loading activities are particularly at risk [63]. The exposure to vapours severely lead to long-term health issues and skin irritation [62]. Vapour recovery systems reduce the risks by recovering emissions at the source, supporting OSHA hazardous exposure standards and reducing risks to workers [63]. Volatile organic compound emissions pose serious threats to both occupational health and environmental quality. The emissions mainly come from chemical and petrochemical manufacturing, where hydrocarbons such as aromatics, alkanes, and alkenes govern the emission shapes. The health influences are reflective, upsetting both surrounding communities and workers over cancer-causing and non-carcinogenic risks. Alkanes and aromatics establish most of the vapour emissions, particularly with aromatics, which are harmful because of their cancer-causing characteristics [64]. The concentration ranges in different industries vary, ranging from 1.16 to 155.59 mg/m³, with massive contributions from halocarbons and alkenes. Workers in chemical industries aspect raised respiratory risks, reproductive, and other general health matters due to constant contact with volatile organic compounds [65]. Specific compounds such as benzene and 1,3-butadiene are associated with high hazardous risks, mainly in industrial surroundings [66]. Neighbouring societies practice bigger health risks due to industrial vapour emissions, as well as vehicle exhausts can contribute significantly to air pollution [67]. Volatile organic compounds help in ozone formation and minor organic aerosol generation, worsening atmospheric pollution and are concerned with their antagonistic impacts [65].

2.4 HYDROCARBON VAPOUR EMISSIONS IMPACTS ON THE ENVIRONMENT

The vapour emissions eco-friendly influence, while crude oil loading into tanker trucks is a noteworthy concern, mainly due to the release of VOCs. These VOC emissions cause air pollution and pose health risks and financial losses. Numerous studies have painted the extent of these emissions and highlighted the need for operational control approaches. For example, gas emissions will reach up to 330 tons of volatile organic compounds per (VLCC). Volatile organic compounds are released into the atmosphere, leading to ecological pollutants and occupational health hazards [67]. The toxic VOCs concentration changes with factors like tank pressure and crude oil temperature, affecting gas emissions volume [65]. VRUs can recover more than 90% of vapour emissions, significantly reducing ecological influences [35]. The application of VRUs is critical, particularly in complex surroundings where oil transportation is increasing [68]. Progressive methods, like Differential Optical Absorption Spectroscopy, are set to display VOC emissions from tankers, offering data for vapour emission foundation strength calculations [69]. Current researches object to illustrate vapour emissions from shuttle tankers, presenting the necessity for inclusive data to inform reduction strategies [70]. While addressing VOC emissions and advancing recovery technologies is crucial, it is also critical to reflect the wider context of oil transportation and the likelihood of substitute energy sources to decrease dependence on fossil fuels, thereby lessening environmental influences and providing prolonged sustainability.

2.5 OCCUPATIONAL HEALTH IMPACTS OF HYDROCARBON VAPOUR EMISSIONS

Vapour emissions during oil loading onto tanker trucks pose significant health hazards, primarily due to exposure to volatile organic compounds (VOCs) such as benzene, toluene, and xylene, which are known toxicants. Research has shown that vapour emissions from petroleum distillates result in both acute symptoms and long-term health problems in workers, particularly terminal staff and tanker truck drivers [71]. In a study by Xaver Baur [72]Acute effects such as dizziness and headaches were observed in 85% of coastal tanker crew members exposed to cargo vapours. Prolonged exposure has been associated with severe health consequences, including respiratory dysfunction, neurological disorders, and haematological abnormalities [73]. Notably, some VOCs—especially benzene—are classified as human carcinogens by the International Agency for Research on Cancer (IARC), with long-term exposure linked to increased risks of leukaemia and other blood cancers. Inhalation of VOCs has also been implicated in liver and kidney toxicity, immune system suppression, and reproductive disorders, depending on concentration and duration of exposure. The application of vapour recovery systems (VRS) has significantly reduced contact levels for oil tanker truck drivers. For instance, mean concentrations of open-chain hydrocarbons decreased from 65 mg/m³ to 8.3 mg/m³ following VRS implementation. This reduction highlights the effectiveness of engineering controls in lowering occupational exposure and associated health risks during oil loading operations. Vapour emissions during filling operations not only intensify environmental pollution but also present persistent occupational hazards, necessitating enhanced exposure monitoring, worker training, and continuous evaluation of protective measures [74]. While studies have documented the acute and chronic health risks of vapour exposure, further emphasis is needed on the efficacy of mitigation strategies—particularly vapour recovery systems—in improving long-term occupational safety outcomes.

2.6 ECONOMIC AND OPERATIONAL CONSIDERATIONS IN VAPOUR RECOVERY SYSTEMS

2.6.1 ECONOMIC ASPECTS

Although vapour recovery systems (VRS) require substantial upfront investment and ongoing maintenance, their long-term economic benefits often justify the cost. By recovering up to 90% of hydrocarbon vapours during truck loading operations, these systems can recover hydrocarbons equivalent to several hundred barrels of oil per operation, depending on the terminal's scale and loading frequency [32]. This translates into considerable economic value when considering market prices and cumulative recovery over time. Moreover, these systems reduce product loss and support revenue retention by capturing vapours that would otherwise be lost to the atmosphere. Financial evaluations of VRS installations often consider indicators such as net present worth (NPW) and profit before tax to assess their economic feasibility [78]. Hermas Abudu [79] Emphasises that investing in vapour recovery systems represents a viable long-term strategy to safeguard revenue, improve product utilisation, and ensure compliance with emission regulations, particularly in facilities processing large volumes of crude oil or refined products.

2.6.2 OPERATIONAL ASPECTS

From an operational standpoint, vapour recovery systems contribute significantly to the efficiency and safety of loading operations. They minimise the need for subsequent treatment of volatile organic compounds (VOCs), streamline the loading process, and reduce environmental hazards at the terminal. VRS also help maintain product quality by preventing contamination through vapour loss, ensuring the loaded product meets required specifications [75]. Operational designs may vary; active systems utilise compressors and condensers to maximise recovery efficiency but require more complex infrastructure and energy input. In contrast, passive systems rely on vapour-balanced loading and are simpler to operate, though generally less efficient [32]. Implementing strategies such as leveraging fluid energy and increasing run-time durations can further reduce operating costs [75]. Moreover, regular monitoring of vapour pressure and system performance helps prevent gas flaring and unplanned emissions, thereby enhancing both safety and productivity during terminal operations [77].

2.7 RESEARCH GAPS AND FUTURE DIRECTIONS

Although (VRS) used during crude oil loading operations have been broadly studied, several serious gaps remain in the existing study. These gaps underscore the necessity for constant study, as well as suggest promising avenues to enhance the operational, environmental, and financial performance of these systems. As vapour recovery units undergo long-term use, troubles like wear and tear, decreased effectiveness, and higher maintenance costs possibly influence the overall efficiency of the recovery process performance. Studies focusing on the durability of VRUs maintenance, which is considerably crucial to identify the optimum way to obtain their effectiveness over time. According to R. J. Simmons [76], studies concentrate on assessing economic and environmental impacts to reduce the energy consumption and maintenance expenses, aiming for VRU operation longevity and offering visions into longer feasibility. Upcoming studies can focus on VRUs tracking the performance over several years to recognise possible areas for enhancement and to advance new maintenance approaches to prolong the systems' lifespan [77]. A noteworthy gap in the current study lies in the VRU's long-term effectiveness and maintenance. Whereas much of the existing works rely on the primary performance and efficiency of vapour recovery units, there is an outstanding lack of research investigating their long-term operational efficiency [76]. Particularly, many researchers supervise the way that these units withstand their performance over prolonged periods, specifically in stimulating or variable working conditions [80]. There are restricted studies on the potential benefits of innovative technologies; an obvious gap in this research is the VRS integration of emerging technologies, while the conventional recovery unit's technologies are globally recognised and established. Developed technologies such as automated modification, timely manner and timely monitoring have the potential to expressively improve system effectiveness. These technologies can help constant monitoring, providing operators with actionable insights to avoid system failures and improve rates of recovery [77]. According to Hermas Abudu [79], Upcoming research should investigate their integration to advance vapour recovery efficiency, minimise maintenance costs and decrease downtime. In addition to that, integrating the progression of predictive models can simplify the performance estimation system and improve total reliability, but there still exists a gap in understanding the regional disparities in the installation and effectiveness of VRS [76]. The numerous studies on VRUs were conducted in regions with robust regulatory frameworks, like the United States and Europe. Though limited studies have relied on the approval and performance of VRUs in developing countries with less strict environmental regulations [76]. In several of these territories, vapour recovery technologies can be widely hindered due to financial constraints. Improper infrastructure or less severe implementation of environmental values. Consequently, understanding the contests and chances related to implementing VRUs in evolving markets is serious. Future studies should examine the barriers to the adoption of VRUs in these regions, including aspects such as installation and operational costs, challenges related to regulatory compliance, and public awareness of environmental problems. Research focused on approaches for the operative application of vapour recovery units in regions with restricted regulatory oversight could expressively assist in advancing global adoption of VRUs technologies and optimising global efforts to mitigate VOC emissions. Additionally, while the majority of the present research concentrates on the environmental advantages of VOCs recovery, there is a necessity to conduct further studies on the economic influence of vapour recovery systems. Research has indicated that, as per several conducted studies, VRUs can recover up to 95% of hydrocarbon vapours, but still, there is a gap in evaluating the continuous ecological benefits of these systems beyond the initial capital asset and repayment periods. The future research prioritises the comprehensive economic analyses of VRUs and evaluating the total cost of ownership. Including the initial installation costs as well as the long-term operational savings from recovering wasted hydrocarbons. Moreover, researchers should explore the economic incentives for adopting VRUs in regions with limited regulation frameworks, highlighting the economic advantages for the local economy and the petroleum industry [69]. Another case where research persists is the integration of VRS with other emission control technologies. Most of the current researches rely on vapor recovery units as an independent system; though, joining vapor recovery with other air quality supervision resolutions, like carbon capture or gas treatment flue which can reduce emission impact, for example VRS integration method with carbon capture systems possibly the capture and storage of gases, thus massively advancing the environmental performance of crude oil loading operations. Researching the synergies between other emission control systems and vapour recovery units potentially provides valuable insights into the way that a holistic approach to air quality management could be advanced in the industry [66]. Upcoming research can also investigate the various VOCs emissions control technologies for an effective integration, aiming to establish a comprehensive environmental control resolution that addresses a variety of quality concerns from greenhouse gases and VOCs emissions. Lastly, there is an absence of standardized performance metrics for VRS, mainly once it comes to associating vapor recovery units across various geographical regions and operational environments, most of the researches measure the effectiveness of the recovery units in terms of emission mitigation rates, but there is lack of consistent standardization in way that these metrics are being considered and calculated, hindering meaningful to compare systems between different contexts. Creating consistent metrics for assessing the performance of vapour recovery units can help to level their efficiency and boost wider acceptance of optimum practices in the oil industry. Furthermore, uniform standards will empower the vapour recovery technologies, allowing the industry to instrument systems that align with combined global standards [79]. Upcoming investigations would attention on emerging standardised assessment frameworks for VRUs that consider reasons like type of system, geographical location, and controlling environmental compliance to guarantee reliable performance valuation between different settings. Even though vapour recovery systems have made noteworthy steps in identifying the environmental, economic, and safety benefits. Future researches focus on long-term working VRUs' performance and the developed integration methods with regional adoptions, the financial influences of vapour recovery, and the advancement of consistent performance metrics. Identifying these gaps will optimise the systematic consideration of vapour recovery systems, as well as contribute to further effective, maintainable, and economically practical resolutions to mitigate gas emissions in the petroleum industry.

3 METHODOLOGY

The efficiency of vapour recovery systems (VRUs) during crude oil loading operations is assessed in this study using a mixed-method approach that combines quantitative emission measurements, qualitative health and safety evaluations, and field-based engineering analysis. The study centres on a real-world example from an operational oil loading port that has an H_2S scavenging unit and a truck-mounted vapour recovery system.

3.1 CASE STUDY (ONE OF KURDISTAN'S OILFIELD LOADING VRUS)

The facility installed a state-of-the-art Vapour Recovery Unit (VRU) system, especially made for loading crude oil into road tankers, according to industry best practices for vapour emission control. In addition to reducing emissions of volatile organic compounds (VOCs), this system neutralises dangerous substances like hydrogen sulfide (H_2S), a substance of great concern because of its acute toxicity and regulatory ramifications. Hydrocarbon vapours produced during oil transfer are routed to the V-860 blowcase at the loading platform, where the vapour management procedure starts. Condensable liquids are gathered and returned to the tanker in this vessel, which serves as a preliminary phase separator, guaranteeing that only the vapour phase proceeds downstream. Vapours are transported from the blowcase to the V-820 H_2S scavenger vessel by blowers K-820A/B. A specific H_2S scavenger reagent is used in this vessel to atomise the vapour stream. The reagent is sprayed through a sprinkler system that is placed at the top of the unit. P-820 pumps the reagent from TK-820 into the system, and P-825 controls surplus reagent by responding to level signals (LSH-8201 and LSL-8202) for accurate inventory control. Before the vapour stream is released, the majority of the H_2S is successfully removed by the neutralisation reaction. Purified vapours are released through the VS-830 vent stack once H_2S is removed. Even while this procedure greatly lowers the quantity of dangerous chemicals, such as H_2S and other VOCs, it's crucial to understand that some hydrocarbons may still be present in the effluent stream. Even after being diluted to trace levels, these residuals may still present slight health and environmental hazards, especially in enclosed or poorly ventilated spaces with little opportunity for dilution and dispersion. This emphasises how crucial it is to keep an eye on things and follow safety procedures even after basic emission treatment. The system functions with precise control mechanisms, as seen through our SCADA interface and described in the procedure P&ID. To ensure both treatment efficacy and operational safety, ideal conditions are maintained using pressure sensors (PG-8200) and level gauges (LG-8200). The total setup is a prime example of an active vapour recovery system, which uses chemical treatment and mechanical compression to efficiently control emissions. In addition to showing adherence to occupational health and environmental regulations, this case also shows proactive steps taken to protect staff and lessen the facility's environmental impact. But in order to frame a true and scientifically informed view of vapour recovery effectiveness, it is imperative to acknowledge the non-zero residual emission. Figure 4 shows the diagram illustrating the sequence of operations, monitoring points, and control systems.

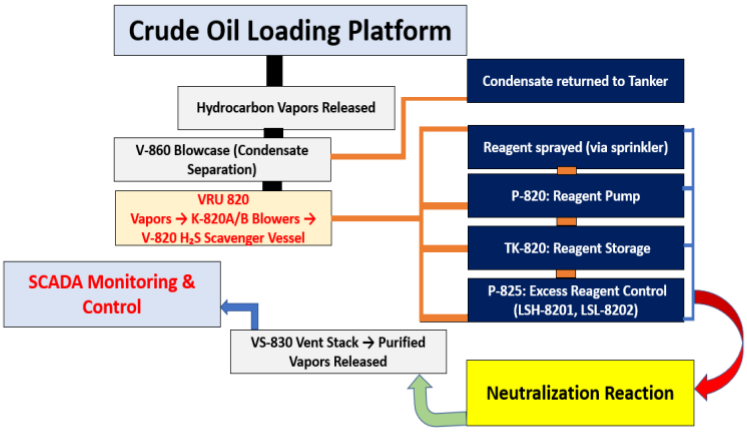

FIGURE 4. Truck loading VRU sequence of operations, monitoring points, and control systems

3.2 ASSESSMENT OF PROCESS FLOW

The vapour recovery procedure was evaluated using:

- P&ID Analysis: A thorough review of instrumentation and piping diagrams to comprehend how VRU components are functionally connected.
- SCADA Data Review: To assess operational effectiveness and pinpoint emission sources, real-time system data (temperature, pressure, and level) was examined.
- Manual Nitrogen Purging Observation: The frequency, efficacy, and operating safety of the blowcase condensate return procedure were evaluated.

3.3 MONITORING OF AIR QUALITY AND EMISSIONS

During loading activities, measurements of the air quality were made at multiple locations:

- Before VRU Entry: To ascertain the composition of raw vapour (with an emphasis on VOCs and H_2S)
- After-Scavenger Ship: To assess the effectiveness of scavenging.
- At the Vent Stack: To assess residual emissions and make sure that the legal limits are being followed.

Sampling was done using OSHA ID-141 for H_2S detection and USEPA Method TO-15 for VOCs. Photoionisation detectors (PID) and portable gas chromatographs were among the tools utilised.

3.4 EVALUATION OF OCCUPATIONAL EXPOSURE

A concurrent assessment of the risk to occupational health was conducted by:

- Monitoring of Worker Exposure: Area detectors and personal gas tags worn by loading staff were used to gather data on short-term and long-term VOC/H_2S exposure.
- Health Symptom Surveys: Tanker drivers and terminal employees were given anonymous questionnaires to complete in order to record symptoms (such as headache, nausea, and dizziness) associated with vapour exposure.
- Characterisation of Risk: The collected data was compared to the ACGIH and OSHA acceptable exposure limits (PELs).

3.5 INTERPRETATION AND ANALYSIS OF DATA

Descriptive and inferential statistical techniques were applied to all obtained data to assess emission levels and exposure concentrations. The central tendency and variability of VOC concentrations before and following VRU installation were summarised using mean and standard deviation. Paired sample t-tests were employed to evaluate the statistical significance of emission level changes, and the results were interpreted using a 95% confidence interval. In order to measure the efficacy of the vapour recovery system over time and emphasise decreases in average emissions, a comparison analysis was also carried out. In order to ascertain whether changes in air quality were correlated with a decrease in workers' unfavourable health reports, Pearson correlation analysis was utilised to investigate the link between reported occupational health symptoms and emission control efficiency.

3.6 IMPACT ASSESSMENT FOR SAFETY AND THE ENVIRONMENT

The residual emissions released from the vent stack were evaluated to assess their environmental and safety implications. These emissions were found to contribute to the degradation of ambient air quality, particularly in areas with limited dispersion. From a safety perspective, the potential accumulation of residual gases in enclosed or poorly ventilated spaces poses a significant ignition and explosion hazard. This underscores the importance of continuous monitoring and maintaining proper ventilation around vapour release points. Sustainability measures were also assessed by comparing emission levels to baseline operations. The improvement was quantified in terms of the mass of VOCs recovered per cubic meter of crude oil loaded, demonstrating a measurable reduction in emissions and enhanced environmental performance.

4 RESULTS AND DISCUSSION

The application of vapour recovery systems (VRS) during crude oil loading operations has led to substantial reductions in vapour emissions. In several field studies, VRS units recovered more than 90% of vapour emissions during standard operations, with some high-efficiency systems achieving recovery rates of up to 95% [32]. These reductions were particularly critical in high-emission zones, such as areas adjacent to storage tanks and loading platforms, where vapour concentrations tend to peak. Air quality improvements were documented in proximity to these high-activity areas, reflecting a measurable reduction in localised environmental contamination. For example, in a terminal-based study cited by Junfeng (Jim) Zhang [67], vapour emissions during VLCC (Very Large Crude Carrier) loading operations were estimated to reach up to 330 tons, underscoring the scale of emissions prevented through VRS implementation. Occupational exposure was also significantly mitigated. After VRS deployment, the geometric mean concentration of aliphatic hydrocarbons among workers dropped from 65 mg/m³ to 8.3 mg/m³ [79]. This reduction correlated with a marked decline in health complaints, particularly respiratory and neurological symptoms. A study by R.J. Simmons [76] reported that before VRS installation, over 85% of coastal tanker crew members experienced headaches and dizziness during loading operations. Following VRS implementation, the prevalence of these symptoms dropped substantially, highlighting the health benefits of emission control. Moreover, benzene exposure—a known carcinogen—was significantly reduced, contributing to lower long-term cancer risks and respiratory complications. From an economic perspective, VRS adoption helped the petroleum industry recover valuable hydrocarbons, which were either reintegrated into production processes or sold for commercial use. These systems also reduced regulatory penalties for VOC non-compliance, providing additional economic motivation for adoption. Beyond VOCs, VRS contributed to reductions in methane and non-methane hydrocarbons, supporting air quality goals and climate mitigation strategies. By incorporating real-time monitoring and predictive maintenance, operators achieved enhanced operational efficiency, reduced downtime, and improved system reliability. Furthermore, emerging integrations with carbon capture and flue gas handling technologies demonstrate the potential for multi-layered emission strategies, promoting more comprehensive environmental protection [76]. However, adoption of VRS technologies varies significantly across regions. In developed regions such as North America and Europe, strict environmental regulations, coupled with financial incentives and technical infrastructure, have facilitated widespread implementation. In contrast, developing countries often face challenges such as limited capital investment, lack of regulatory enforcement, infrastructure deficits, and technical expertise gaps, which hinder the large-scale deployment of VRS. These disparities underscore the need for targeted policy support, capacity building, and international cooperation to promote equitable access to emission-reduction technologies. Table 3 presents a summary of the study’s key findings, highlighting measurable differences in environmental, health, economic, and technological outcomes before and after the application of vapour recovery systems in crude oil loading operations. Few studies offer long-term empirical assessments of VRS efficacy across various climates or material kinds, despite its proven advantages. Comparative information regarding the cost-effectiveness of active and passive systems in areas with inadequate infrastructure is particularly scarce. Furthermore, the integration of AI-based diagnoses with real-time emission monitoring is still a new yet unexplored field. The standardisation of monitoring procedures, life-cycle economic evaluations across various regions, and field validation of VRS efficiency under harsh working conditions should be the top priorities of future research. Together, industry and regulatory organisations should create scalable methods for the deployment of VRS in poor nations, backed by funding and technical assistance. Despite the success of VRS adoption, there are still a number of operational and research limitations. System performance and durability under various environmental conditions and crude compositions have not been evaluated in many long-term experiments. Furthermore, there is a lack of reporting on the cost-benefit analysis of active versus passive systems in areas with limited resources. Additionally, the current SCADA or DCS frameworks do not fully integrate sophisticated digital tools like AI-driven leak detection or predictive analytics.

Future studies should concentrate on the following to further the field:

- Verification of VRS performance in the field under harsh and changing circumstances.
- Models of regional economic viability.
- Creation of standardised procedures for reporting and monitoring emissions.
- Techniques for scalable implementation in places with limited infrastructure, such as financial support systems and training.

Taking these actions can make sure that VRS adoption is both realistically possible and supported by science in a variety of international contexts.

Table 3. The effect of Vapor Recovery Systems on Crude Oil Loading Operations

Influence of Vapour Recovery Systems (VRS) on Crude Oil Loading Operations			
Category	**Pre-VRS**	**Post-VRS**	**Additional Info**
VOC Emission Mitigation	0% mitigation (Baseline)	90-95% mitigation	330 tons of VOCs dropped per VLCC loading
Economic Influence	No savings	Cost savings from VOC capture and fines	Income from recovered hydrocarbons
Technological Advancements	None	Timely monitoring, analytical maintenance	Reduced downtime, better recovery rates
Environmental Influence	High VOC emissions	Reduced methane & VOC emissions	Enhanced air quality, reduced ground ozone
Occupational Health Influence	85% workers report symptoms	Hydrocarbon levels: 65 mg/m³ → 8.3 mg/m³	Acute symptoms: headaches, dizziness

CONCLUSION

Vapour recovery during crude oil filling operations is critical in addressing both ecological and occupational health challenges. The volatile organic compounds (VOCs) emissions and other hydrocarbons through these operations significantly lead to atmospheric pollution and climate change, and pose risks to public health. Nevertheless, the application of VRS technologies, like VRUs, has proved a considerable decrease in vapour emissions, reducing these environmental and safety issues. The discoveries from this research emphasise the efficiency of VRUs in catching up to 95% of released hydrocarbons, mitigating harmful emissions, as well as recovering valuable hydrocarbons that will otherwise be wasted. This process improves functional effectiveness and offers financial benefits through advancing product yield and reducing economic wastes linked with product wastage and emission consequences. Studies have illustrated that the VRS installation expressively improves work-related health concerns by mitigating worker contact with destructive vapours, such as classified carcinogens. Studies have specified that VRUs noticeably decrease the harmful vapour concentration in work surroundings, thus mitigating the occurrence of acute and long-lasting health concerns among workers. Regardless of the clear environmental and health advantages, the adoption of VRUs differs significantly between nations. In developed regions, controlling agendas care about the integration of VOC regulation technologies, whereas numerous developing countries face substantial challenges, like economic restrictions and insufficient infrastructure. These points to the need for continued research into cost-effective solutions and regulatory policies that can promote the broader adoption of vapour recovery systems on a global scale. In conclusion, VRS is integral to improving air quality, advancing occupational health and fostering economic resilience within the oil and gas industry. The continual advance of improved recovery technologies, alongside the founding of solid regulatory structures and improved international association, will be fundamental in accomplishing wider environmental sustainability and improving public health conditions. As the oil and gas industry continues to expand, the role of vapour recovery in mitigating emissions and enhancing operational efficiency will be critical in driving sustainable practices within the sector. With the ongoing growth of the oil and gas industry, the importance of VRS in efforts to reduce emissions and advance operational efficiency will be crucial in supporting sustainable practices across the industry.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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