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Use of sensors in air intake in internal combustion engines: A systematic review of the literature

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ABSTRACT
Due to constant contact with the earth, many agricultural machinery that have diesel engines, present problems in their performance due to the ingress of dust particles into the air intake system. This work proposed to perform a systematic review of the literature regarding the use of sensors in the solution of contamination problems in the air intake system in diesel engines. The inclusion criteria were complete articles available in English and Portuguese, which had some application regarding the use of sensors in diesel engines, or which dealt with problems in air intake. The exclusion criteria, on the other hand, were the studies that did not fit these eligibility criteria. About 2,414 articles were retrieved, of which 31 met the eligibility criteria and were accepted for full reading. Given the limitations of the research, such as a small number of databases used, restriction of the language of the works, a meta-analysis was not possible to be conducted, limiting the research to only qualitative analyses. However, it was possible to notice some gaps in knowledge regarding the lack of works aimed at solving the problem raised, as well as the lack of works related to the theme at the national level.

Keywords: Air intake, Engine, Diesel Engines, Dust, Systematic Review.

1 INTRODUCTION

The diesel engine was patented in 1892 by the French engineer Rudolf Diesel, and since then it has been widely used in various applications, mainly in agricultural machinery. Due to the high performance that the engine presents, this contributes to the reduction of expenses, especially in fuel. In addition, the engine provides a longer duration of the equipment, and still has low maintenance costs making this type of engine a preference for use in heavy vehicles (Rosa, 2014).

The lubricant, used in diesel engines, perform important functions such as: shock damping and noise reduction (Tanaka, 2014); minimization of friction between parts providing a significant reduction in wear; decreased heating of frictional components – heat absorption; facilitation of starting at low temperatures, reduction of pressure loss from the combustion chamber, sealing the clearance of piston segment rings (Santos et al, 2014; Padovan & Angels, 2012); formation of lubricating film on the parts to protect against corrosion and formation of deposits, prevent the entry of impurities and act as a cleaning element (Junqueira & Oliveira, 2013).

Predictive maintenance by lubricant oil analysis, which aims to prevent failures through monitoring and monitoring of various parameters, which allows greater availability of equipment and reduction of costs related to maintenance (Kardec & Nascif, 2010), and is performed by monitoring the chemical and physical conditions of the lubricant, observing the presence of contamination by water molecules and / or presence of particles in the sample (Santos et al., 2014).

Gasparini (1983) states that, although the periodic analysis of oil is one of the best auxiliary systems for monitoring and controlling equipment, one should not expect the elimination of all problems with this method alone. In relation to the wear caused in the engines, (Kimura, 2010), in a study of analysis of lubricating oil in diesel engines, cites silica – from dust contamination – as one of the particles of greater wear, which compromises the useful life of the engines, with long periods of repairs and very high cost.

Currently, silica is detected only through laboratory analysis of the lubricant, which takes about 10 days to deliver the results, and often the engine can fail even before the arrival of these results, which causes losses to the agro-industrial sector directly reflecting on the cost of production and the final value of agricultural production.

Although Brazil is considered an agricultural country, in searches in the databases containing the Search String sensor AND air AND "internal combustion engine" did not recover works done at the national level, evidencing the need to carry out a new research in order to understand the State of the Art regarding the application of Instrumentation in agricultural machinery in the solution of problems as previously mentioned.

In view of the importance of agriculture for the country's economy, and the contextualization of the problem, the objective of this study was to present the evolution of the literature on the use of sensors in internal combustion engines, such as Diesel, through a systematic review methodology. Throughout the work are discussed the types of sensors and technologies used in the solutions of problems related to these types of engines, the methods used, the geographical distribution of the works recovered by the research, and the results obtained by them. In addition, the gaps found in knowledge are presented, especially in relation to the use of sensors in air intake systems of these engines, with recommendations for future investigations.

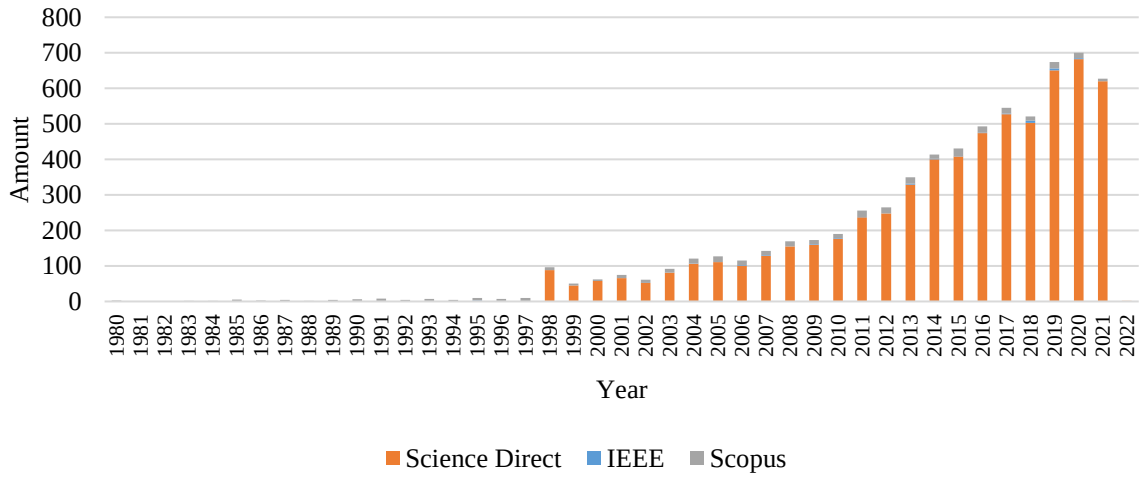
2 METHODOLOGY

Lubricating oil is the element that most affects the life of an engine, as it is responsible for the lubrication of various parts of the mechanism and this influences the operation and wear of the parts. However, when the engine is contaminated by dust particles (silica), these particles affect the operation as they interfere with the viscosity and the action of promoting the cleanliness of the engine. These functions are the responsibility of lubricating oil (Mello, 2015). With this it is necessary to understand the contaminations in the lubricants and the consequences in the engines, so it is important to carry out a Systematic Review of the Literature (RSL) on the subject to obtain the proposed results.

Systematic Literature Review is a study method that applies strategies to, from a database of files related to the theme, select, analyze, evaluate and synthesize the works so that a consistent study of the theme is carried out and thus even define directions for future research. Before conducting a systematic review, it is necessary to create a research protocol. It is recommended that the protocol be registered in some database, being available to other researchers, so that it is possible to avoid wasting the time of other researchers or groups of systematic reviews in carrying out a review that will be or is already being conducted, thus avoiding the duplication of research that answers the same question. In addition, it also demonstrates the transparency of the study and allows for reproducibility (Barbosa et al, 2019).

To perform this RSL, we first searched the IEEE Xplore, Science Direct and Scopus databases, all the papers published in recent years, where the results of this search are shown in graph 1. In the graph it can be noted how research related to the theme has developed in an increasing way and in the year 2021 there were 700 publications, most in the Science Direct database, thus evidencing the interest and relevance in studying the theme.

Graph 1 - Works retrieved with the search strategy in the three databases since 1980



Source: Authors (2022)

In graph 1, in addition to showing the number of published works, it is also possible to visualize

how the number of published works has developed increasingly since 1998.

From the data was carried out the processes of analysis of the works, this process of analysis developed in three stages: input, processing and output. For the accomplishment of the steps was used the software StArt (State of the Art through Systematic Review) which is a free software, which was developed in the Laboratory of Research in Software Engineering of UfScar. The StArt software divides the study into three phases: protocol, execution and summarization and after completing all the phases we have the files selected for continuity of the RSL.

The first filter used for the research was the inclusion of works recovered from the year 2017. And then, the selection of only original articles for systematic review. Table 1 illustrates the quantities found in each of the databases, as well as the number of original articles recovered from the year 2017.

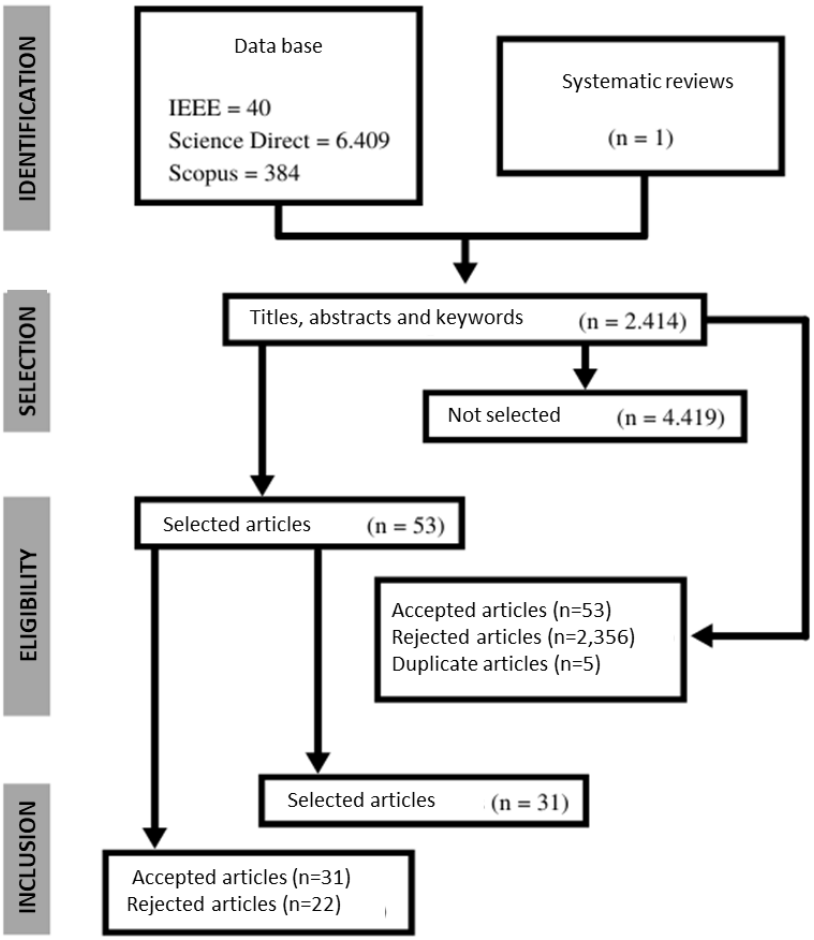
Table 1 - Results of the application of the search strategy in the databases

Databases	**General**	**As of 2017**	**Original articles**
IEEE	40	16	0
Science Direct	6.409	2.985	2.382
Scopus	384	68	32
TOTAL	**6.833**	**3.069**	**2.414**

Source: Authors (2022)

Figure 1 shows the flowchart with the distribution of articles by database indicating the path of the selection where the result of the studies to be used to perform the RSL was obtained.

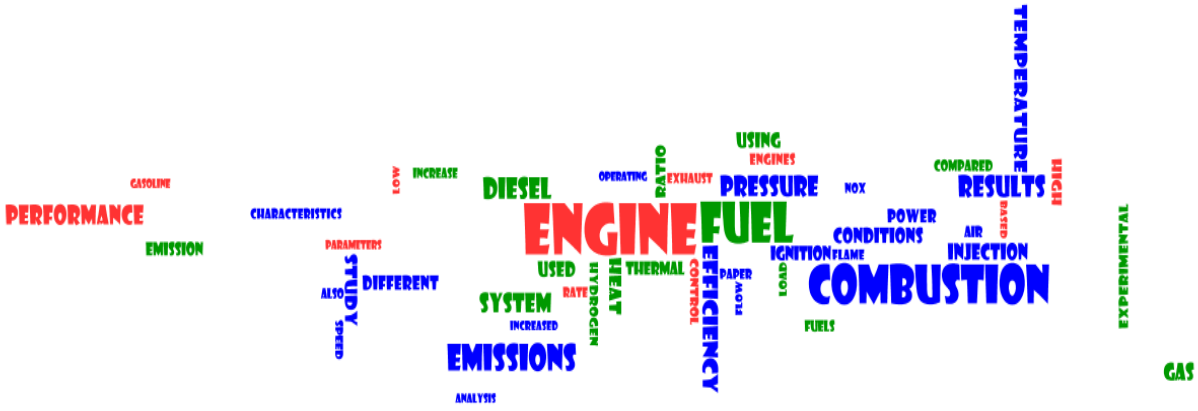
Figure 1 - Flowchart of the original articles included



Source: Authors (2022)

In the inclusion stage, of the extracted articles, the software obtained the word cloud found in the abstract as shown in Figure 2. It is possible to notice the following words highlighted: Engine, Combustion, Fuel, Emissions, Pressure, Efficiency, Results and Temperature.

Figure 2 - Word cloud found in the abstracts of the works after the extraction step



Source: Authors (2022)

3 RESULTS AND DISCUSSION

Of the works selected for analysis, after verification of the abstracts of the works, following the criterion that the abstract presents study, development and result, after analyzing all the works, 31 works were selected to perform the RSL. Chart 1 presents the information of the works selected for the review where a report is presented containing the authors, year of publication, title and synthesis of the authors' study, as well as method and results obtained study by study so that an analysis can be carried out on the studies carried out on the subject.

Given the initial interest regarding the use of sensors applied in internal combustion engines, especially in the detection of dust particles, it is noted in the works only one article addressing this problem, more specifically the work of Maddineni, Das and Damodaran (2017), who performed a comparison between two types of filters, one treated with oil, and another more traditional made of paper fiber. However, it has no application of sensors for the solution of the problem.

Of the articles studied, about 26% deal with greenhouse gas emissions generated by diesel engines, 16% deal with fault tolerance, another 16% deal with calibration and engine performance, 16% deal with the release of heat and pressure in the cylinder, 3% deals with the issue of dust in the air intake (but without application of sensors), and about 10% deal with other approaches such as vibrations, noise pollution, applications to educational contexts (not directly linked to engines), and cavitation.

Frame 1 - Selected articles for RSL

No.	Author(s)	Title	Local	Proposal	Application
1	Jatana, G. et al. (2017)	Design and development of a probe-based multiplexed multi-species absorption spectroscopy sensor for characterizing transient gas-parameter distributions in the intake system of I.C. engines	USA	Use of a multiplexed, probe-based multispecies absorption spectroscopy sensor used to characterize gas parameter distributions in internal combustion engine air intake systems.	Internal combustion engines
2	Prima, E. C. et al. (2017)	Heat Transfer Lab Kit using Temperature Sensor based Arduino for Educational Purpose	Indonesia	Use of Arduino laboratory kit to measure heat transfers.	Engines
3	Zhai, Y. et al. (2017)	A Soft Sensor-Based Fault-Tolerant Control on the Air Fuel Ratio of Spark-Ignition Engines	China, Thailand	A new scheme for controlling the air/fuel ratio was proposed, using artificial neural networks, based on fault detection, promoting a satisfactory result in relation to engine performance.	Spark ignition engines

4	Wong, P. K. et al. (2017)	Efficient point-by-point engine calibration using machine learning and sequential design of experiment	China	In order to reduce the experiments performed for calibration of modern engines, a point-to-point calibration approach of the engine was proposed, based on machine learning methods.	Engines
5	Cuyper, T. D. et al. (2017)	Evaluation of empirical hear transfer models using TFG heat flux sensors	Belgium, United Kingdom	Evaluation of heat transfer using models of heat flow sensors inside engine cylinders.	Internal combustion engines
6	Omar, F. K. et al. (2017)	Time and frequency analyses of dual-fuel engine block vibration	United Arab Emirates, Egypt	Analysis of the time and frequency of motors in order to investigate vibrations that occur in these types of engines. Comparisons were made on dual-fuel engines with diesel engines, showing that dual-fuel engines had better mechanical performance due to a lower vibration frequency.	Diesel Engines
7	Zhang, M.; et al, (2017)	Acoustic wave propagation in a sensor port: Experimental measurements and analytical model predictions	USA	Measurement of pressure fluctuations, through the use of sensor, to detect the propagation of acoustic waves and thus make predictions about this type of problem.	Engines
8	Dogru, B. et al. (2017)	Electronic measurement of weather conditions for an engine test room	Turkey	Use of Arduino microcontroller to measure climate conditions in an experiment room, and assess the influence of these conditions in performance tests of internal combustion engines.	Internal combustion engines
9	Corsini, A. et al. (2017)	Internal Combustion Engine sensor network analysis using graph modeling	Italy	Implementation of a complex method of network theory, in order to evaluate the performance of an internal combustion engine, through graphical modeling.	Internal combustion engines
10	Siano, D. et al. (2017)	Diagnostic Process by using vibrational sensor for monitoring cavitation phenomena in a Gerotor pump used for automotive applications	Italy	Use of vibration sensors to monitor the phenomenon of cavitation.	Automotive industry
11	Maddineni, A. K. et al. (2017)	Inhibition of particle bounce and re-entrainment using oil-treated filter media for automotive engine intake air filtration	India	Use of oil treatment in the filter medium in order to reduce the entry of particles that jump into the engine during air intake, especially in vehicles that are in contact with the ground.	Diesel Engines/ Air Intake
12	Bauke, S. et al. (2018)	Optical sensor system for time-resolved quantification of methane concentrations: Validation measurements in a	Germany	Application of a sensing system that can serve as a diagnostic to detect methane concentrations in internal combustion engines that use this gas as a means to reduce emissions and increase the efficiency of this type of engine.	Internal combustion engines

		rapid compression machine			
13	León, P. G. et al. (2018)	Implementation of a fault tolerant system for the internal combustion engine's MAF sensor	Mexico	Implementation of a fault detection system for an air mass flow (MAF) sensor in an internal combustion engine.	Internal combustion engines
14	Battista, D. D. et al. (2018)	Flow and thermal management of engine intake air for fuel and emissions saving	Italy	An evaporator mounted in parallel with the refrigeration unit was placed on the air intake line in order to load cooled air to reduce the temperature of the engine's air intake, thereby increasing its volumetric efficiency due to the increased air density and cylinder filling.	Internal combustion engines/ Engine air intake
15	CheN, X. et al. (2018)	Improvement of engine performance and emissions by biomass oil filter in diesel engine	China	A comparison of the use of modified sawdust lubricating oil filter with traditional paper fiber filters was performed in order to reduce emissions from diesel engines.	Diesel Engines
16	Sujesh, G. et al. (2018)	Modeling and control of diesel engines: A systematic review	India	Systematic review carried out to understand the attempts made in the literature to implement improvements in diesel engines. The study showed, that in recent decades, an effort has been made to increase the performance of these engines, such as decreasing noise and its emissions, as well as heat releases.	Diesel Engines
17	Athanasopoulou, A. et al. (2019)	What technology enabled services impact business models in the automotive industry? Na exploratory study	Holland	Identification of automotive services that impacted business models within the automotive industry through an exploratory study.	Automotive industry
18	Guardiola, C. et al. (2019)	Integration of intermittent measurements from in-cylinder pressure resonance in a multi-sensor mass flow estimator	Spain, USA	Creation of an interactive algorithm capable of reducing the number of operations, along with an adaptive filter to identify faulty measurements and a Kelman filter combined with various sensors and models. Thus, the objective is to measure the resonance of the cylinder pressure, showing a potential application in real driving conditions.	Internal combustion engines
19	Velmurugan, V. et al. (2019)	Prediction of noise, vibration and exhaust gas emission characteristics using palm oil in a four-stroke diesel	India	Use of palm oil to reduce noise pollution generated in diesel engines.	Diesel Engines
20	Han, R. et al. (2020)	Virtual engine in-cylinder pressure sensor for automobiles and agricultural tractors	Germany	A virtual structure to estimate the pressure in the cylinder was built in the passage path of the pressure signal in the cylinder and the vibration signal, identified in the time domain. In order to use the pressure cylinder signal as an important parameter to gauge the	Internal combustion engines

				high performance of internal combustion engines, especially in modern agricultural machinery equipped with such engines. The structure is based on the Kalman filter, which has as input the vibration of the engine structure in operation.	
21	Nguyen, H. K. et al. (2020)	Simulation environment for analysis and controller design of diesel engines	Finland	Use of gray box model technique that can be used to predict the pressure in the cylinders and heat release, factors that decrease the performance of the engine, causing them to emit more greenhouse gases.	Diesel Engines
22	Cao, J. et al. (2020)	Model based control with online automatic adaptation by neural network for advanced diesel combustion	Japan	Creation of an automatic online model that adapts to real driving conditions, in order to control diesel engines, based on neural networks, and thus improve engine performance.	Diesel Engines
23	Singh, V. et al. (2020)	A novel state and parameter estimation algorithm for spark ignition engine	India	A new method was created combining the use of Kalman filters with the method of recursive least squares in order to estimate the physical parameters in an attempt to solve problems in the engines related to control estimates, in order to make them more efficient and less polluting.	Engines
24	Martínez, S. et al. (2020)	Model calibration and exergoeconomic optimization with NSGA-II applied to a residential cogeneration	Spain	Considering the high efficiency of the engine and lower harmful gas emissions, a micro-cogenereaction model based on natural gas internal combustion was proposed.	Internal combustion engines
25	Han, J. et al (2020)	Experimental investigation of ethanol/diesel dual-fuel combustion in a heavy-duty diesel engine	Netherlands, UK, Germany, USA	Use of ethanol from the intake intake, and diesel injected directly into the cylinder of the heavy engine, enabling the operation of dual fuel, in order to improve the performance of the engine and reduce its gas emissions.	Diesel Engines
26	Li, Z. et al. (2020)	Control of intake boundary conditions for enabling clean combustion in a variable engine conditions under intelligent charge compression ignition (ICCI) mode	China	Creation of a dual fuel model called intelligent charge compression ignition.	Diesel Engines
27	Shi, C. et al. (2020)	Comparative evaluation of intelligent regression algorithms for performance and emissions prediction of a hydrogen-enriched Wankel engine	China	Creation of a multi-objective regression model that provides insights into the mathematical relationship between engine performance and control and operation parameters in order to regulate high emissions and increase engine performance.	Hydrogen-enriched Wankel Rotary Engine

28	Shahbaz, M. H. et al. (2021)	Design of active fault tolerant control system for air fuel ration control of internal combustion engines using artificial neural networks	Pakistan	Creation of an active control system for fault tolerance, based on Artificial Neural Networks, for the control system of the air x fuel ratio, in order to enable the rehabilitation of a spark ignition engine.	Internal combustion engines
29	Guan, J. et al. (2021)	Experimental and numerical research on the performance characteristics of OPLVCR engine based on the NSGA II algorithm using digital twins	China	Development of digital twins, using GT-Power software for engines with the OPLVCR mechanism, in order to optimize fuel consumption and reduce greenhouse gas emissions.'	Engines
30	Shi, H. et al. (2021)	Statistical study on engine knock oscillation and heat release using multiple spark plugs and pressure sensors	Saudi Arabia, China	In order to investigate the fluctuations induced by autoignition and heat release, multiple correlations were used to evaluate the maximum amplitude of pressure oscillation, thus constructing a multiple linear regression for prevention and validation of these occurrences.	Engines
31	Gelmini, S. et al. (2021)	Design and experimental validation of three-way catalyst age estimator and Fisher information analysis for optimal sensor selection	USA	A double Kalman filter was developed and experimentally validated to estimate the oxygen storage of three-way catalysts and the age-dependent oxygen storage capacity.	Internal combustion engines

Source: Authors (2022)

Of the articles studied, about 26% deal with greenhouse gas emissions generated by diesel engines, 16% deal with fault tolerance, another 16% deal with calibration and engine performance, 16% deal with the release of heat and pressure in the cylinder, 3% deals with the issue of dust in the air intake (but without application of sensors), and about 10% deal with other approaches such as vibrations, noise pollution, applications to educational contexts (not directly linked to engines), and cavitation.

A highlight for the work of Sujesh and Ramesh (2018), who conducted a systematic review regarding modeling and control of diesel engines. In this study, we also identified some of the most used methods to improve the performance of these engines. Such as noise, emissions, vibrations, robustness and performance problems. They also highlight that the prevalence of the existence of these problems that are still without practical solutions, present evidence of gaps in knowledge, and are areas that need more investments in research.

Another important point that deserves to be highlighted is the fact that no work done in the national territory has been recovered, there is a prevalence of work done in China, USA, India and Italy. These countries were highlighted and presented at least three papers in each country. This

indicates the need for further research at the national level, especially since Brazil is a country with a strong agricultural economy. In addition to the origin of these works, the approaches were very focused on issues raised by Sujesh and Ramesh (2018), with indications of gaps in knowledge for the application of sensors in the detection of particulate matter.

These indications may be the result of the limitations employed during the research design, as well as limitations applied at the time of data processing and selection. A greater scope regarding the search for various types of studies, the non-limitation regarding the language of the works, analyses regarding the indexing of the databases, searches for terms most used in the literature, as well as the increase of searches in more databases could indicate different results. Another point that limited the work was the high heterogeneity between the works recovered and selected for the review.

Due to these differences, it was impossible to perform a meta-analysis to summarize the data of the studies and mathematical and statistical measurement. If the type of study, and treatment is better defined, this will enable deeper and quantified analyses, such as the level of heterogeneity in the uses of sensors to solve problems, analysis of the risks of bias and evaluation of the results obtained by the systematic review performed.

4 FINAL CONSIDERATIONS

Although the systematic review was limited to a more qualitative analysis, and there was no possibility of conducting a meta-analysis of the recovered articles, due to the different types of studies and the non-homogenization of data, it was still possible to notice evidence of some gaps in knowledge regarding the use of sensors to solve problems related to diesel engines, in particular the ingress of dust into the air intake of these engines.

Many approaches adopted in the studies deal with problems related to the performance of these engines, problems with vibrations, noise, heat release, energy efficiency, pressure in the cylinder, only 1 study presented concern about the issue of dust ingress in the air intake of these engines, however without the use of sensors as a proposed solution. Showing evidence of knowledge gaps.

Another factor was the lack of work recovered at the national level, which increases the need for investment in research to solve this problem, since the country's economy is dependent on agriculture. Because of this, a suggestion for future work would be to carry out a study focused on the application of sensors in an attempt to solve the problem that is still recurrent, and even the publication of scientific articles that can serve as a basis for the development of future work aimed at filling the gaps in knowledge regarding the application of sensors in the air intake in diesel engines.

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