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Fuel consumption by agricultural machinery: a review of pollutant emission control technologies

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ABSTRACT: *Most energy used to operate agricultural machines in the field is generated from fossil fuel combustion. The combustion process emits atmospheric pollutants, increasing the emission of greenhouse gases (GHGs). In this context, this review is to discuss technologies for mitigating diesel engine GHG emissions to advance sustainable development in the agricultural machinery sector. This paper presents strategies and technologies widely adopted by agricultural machinery manufacturers in controlling pollutant emissions during fuel combustion. The findings of this study encompass sustainable alternative technologies, such as selective catalytic reduction, exhaust gas recirculation, diesel particulate filter, and fuels. This study helps reveal the environmental impact of agricultural field operations that generate GHG emissions.*
Key words: *greenhouse gases, emission limit, agricultural mechanization.*

Consumo de combustível por máquinas agrícolas: uma revisão das tecnologias de controle de emissão de poluentes

RESUMO: *Grande parte da energia utilizada para o funcionamento das máquinas agrícolas em suas operações no campo ainda é resultante da combustão de combustíveis fósseis. O processo de combustão provoca a emissão de poluentes atmosféricos que contribuem para o aumento dos Gases de Efeito Estufa (GEE). Neste contexto, esta revisão tem como objetivo descrever as tecnologias que contribuem para mitigar as emissões de GEE pelos motores de ciclo Diesel, a fim de contribuir para a compreensão e o desenvolvimento da sustentabilidade no setor de máquinas agrícolas. São apresentadas as estratégias e tecnologias que comumente estão sendo adotadas pelos fabricantes de máquinas agrícolas para o controle das emissões de poluentes, durante o processo de combustão do combustível. Os achados do estudo apresentam as alternativas tecnológicas sustentáveis como a Selective Catalytic Reduction, Exhaust Gas Recirculation, Diesel Particulate Filter, e sobre o uso de combustíveis alternativos. Ainda, contribui para o entendimento do impacto ambiental das operações agrícolas em campo, que provocam as emissões de GEE.*
Palavras-chave: *gases de efeito estufa, limite de emissões, mecanização agrícola.*

INTRODUCTION

Succeeding in large-scale production requires agricultural machinery (VIAN et al., 2013). Agricultural mechanization is inherent to intensive agriculture and may be applied to achieve more sustainable agriculture (BANERJEE & PUNEKAR, 2020). Because of their advantages, such as high efficiency, reliability, durability, and low operating costs, diesel engines are adopted on a large scale in developing agricultural machines (RESITOGLU et al., 2015). Among the major players in the internal combustion diesel-engine market, European Union countries and India stand out, followed by the United States of America, China, Japan, and Brazil (STEINER et al., 2016).

The global market for agricultural tractors was valued at USD 60,468.9 million in 2020 and is projected to reach USD 81,909.0 million in 2026 (MORDOR INTELLIGENCE, 2021). With the increasing popularity of diesel engines in agriculture, Greenhouse Gases (GHG) have increased at the same rate (RESITOGLU et al., 2015). Typically, GHG emissions are attributed to fossil fuels, such

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as coal, natural gas, and oil, in internal combustion engines of agricultural machinery (PAO et al., 2015; TORRES et al., 2020). Therefore, new technological trends to mitigate GHG emissions in agriculture are being adopted in developing agricultural machinery engines (LIAO, 2018). In particular, technological innovations seek to achieve the objectives of environmental policies on permissible limits of pollutants (SILVEIRA et al., 2021) derived from fuel combustion (DALLMANN & MENON, 2016).

The environmental policies adopted in developed and developing countries consider large-scale crop production and appropriate and sustainable approaches to optimize agricultural activities (LOVARELLI & BACENETTI, 2019). New internal combustion engines improve agricultural machinery effectiveness and power and help reduce GHG emissions during fossil fuel combustion (CAVALLO et al., 2014). In addition, new agricultural machines, which comply with pollutant emission legislation, enhance grain productivity and minimize problems related to field operations (RESITOGLU et al., 2015; SILVA et al., 2018).

In China, 60% of mobile emissions are derived from non-road sources (GUO et al., 2020). Therefore, discussions about agricultural machinery emissions are crucial in clarifying pollution sources and developing control strategies (ZHANG et al., 2020) or adopting effective emission mitigation measures (LANG et al., 2018). However, studies on sustainability in the agricultural machinery sector generally focus on identifying the factors influencing the adoption of sustainable agricultural practices (FOGUESATTO et al., 2020) and analyzing solutions adopted to control exhaust gas emissions from tractors and self-propelled agricultural machines (LOVARELLI & BACENETTI, 2019).

Overall, studies on potential technical solutions to reduce emissions from agricultural machinery engines have not been conducted extensively (SCHLOSSER et al., 2020). In addition, further research on legislation regulating off-road engine emissions (HOU et al., 2019; SILVEIRA et al., 2021) and analysis of diesel engine GHG emissions (RESITOGLU et al., 2015) are required.

This literature review is to discuss technologies for mitigating diesel engine GHG emissions toward furthering sustainable development in the agricultural machinery sector. This paper discusses pollutants emitted from agricultural machines and their inhibiting factors. In addition, this review bridges the research gap on the environmental impact of GHG emitted from agricultural machinery.

Diesel engine GHG emissions

GHGs derived from rising atmospheric concentrations (RESITOGLU et al., 2015) have severe environmental impacts and induce catastrophic climate change, including global warming (LOU et al., 2015; HEIDARI & PEARCE, 2016). Diesel engines contribute to the release of GHGs from pollutant exhaust gases such as carbon monoxide (CO), hydrocarbons (HCs), particulate matter (PM), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) (RESITOGLU et al., 2015; KIM et al., 2017).

Emissions from agricultural machinery engines depend on the type of fuel and engine, the working capacity of the engine, the engine technology, and fretting of the mounted parts (LINDEN & HERMAN, 2014). In addition, pollutant emissions from diesel engines directly depend on the fuel consumption under different operating conditions (TSE et al., 2015; JANULEVICIUS et al., 2016) because an increase in fuel consumption proportionally increases the CO_2 emissions (WU et al., 2015). Another aggravating factor is the agricultural equipment using diesel engines manufactured before regulations on permissible emission limits.

Diesel engines are compression ignition engines. Air compression in the combustion chamber increases the temperature. At such high temperatures, the fuel, that is, the mineral diesel oil spontaneously burns when injected into the cylinder. This process uses heat to release the chemical energy of the fuel (calorific value) and thus, convert this chemical energy into mechanical energy (RESITOGLU et al., 2015). The ideal thermodynamic cycle in internal combustion diesel engines generates CO_2 and H_2O (PRASAD & BELLA, 2011). However, factors such as the stoichiometric air-fuel ratio and high combustion temperature generate harmful pollutants (RESITOGLU & KESKIN, 2017). Figure 1 shows the approximate composition of diesel engine exhaust gases.

Significance of controlling pollutant emissions

Exhaust gas emissions directly impact human health, accounting for the increased incidences of illnesses and deaths from cardiorespiratory, neoplastic, and metabolic diseases worldwide. The combustion of fuels such as mineral diesel triggers different health and environmental responses (MANZETTI & ANDERSEN, 2016). According to the World Health Organization (WHO) report, environmental air pollution from the health, transport, agriculture, energy, and urban development sectors was responsible for approximately three million

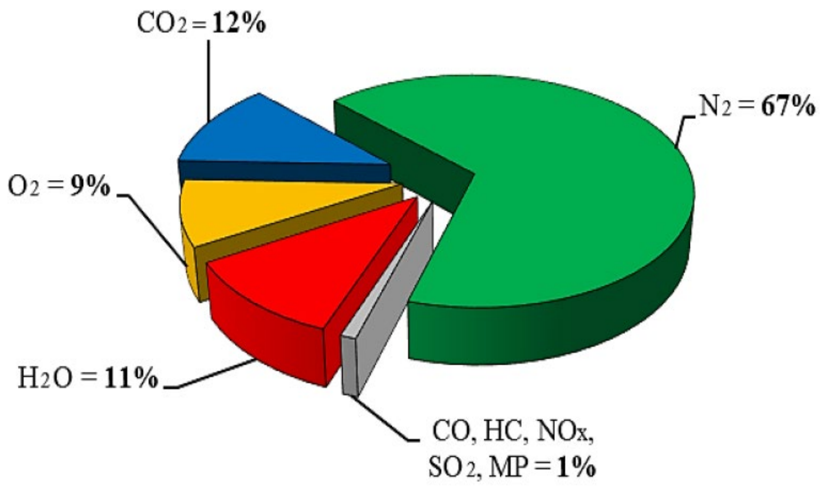

Figure 1 - Approximate composition of exhaust gases from the combustion of Diesel cycle engines.

Source: Adapted from RESITOGLU et al. (2015).

deaths in 2013 (WHO, 2016). Table 1 lists the main pollutants, their origins, and environmental and health problems caused by diesel engine exhaust emissions.

Concerns about the sustainable impacts of anthropogenic activities led to international meetings on climate change. As the international discussion around sustainability guidelines evolved, a global agreement on climate change was reached in 2015 in Paris, France, during the 21st Conference of the Parties (COP21) to reduce GHG emissions (ONU, 2015). Implementing the Paris Agreement is key to mitigating GHG emissions and increasing climate resilience, as 195 countries follow its guidelines and are responsible for developing new measures to achieve the COP21 goals.

Global GHG emissions should be reduced by 50%–85% by2050 to limit heating to 2°C (RESITOGLU et al., 2015). In contrast to previous conferences such as COP3 in Kyoto and COP15 in Copenhagen, COP17 held in Dublin introduced the scope of climate change mitigations. This conference was crucial for sustainable policies and the periods preceding COP21, in which most countries committed to climate action known as Intended Nationally Determined Contribution.

COP21 covered emissions terms, unlike COP3 (ONU, 2015). Compliance with these terms appeared to reduce GHG emissions, but the cooperation between countries to achieve a faster low-carbon economy remains a challenge (VANDYCK et al., 2016). Improvements and reduction initiatives are also expected in the agricultural machinery sector. However, progress in this sector is limited by the lack of compliance with legislation on GHG emission control (SILVEIRA et al., 2021). In addition, many developing countries fail to adopt emission limit standards, as they ignore the internal combustion engines of non-road vehicles. This lack is partly caused by the significant data gap in activity level, emission factors, and other information (GUO et al., 2020).

Pollutant control strategies and technologies

Regulatory programs for agricultural machinery engines (Brazil/PROCONVE MAR1, Japan/Tier3, European Union/Stage5, Canada and South Korea/Tier4f) impose strict limits on pollutant emissions in their initial stages (SILVEIRA et al., 2021). Their guidelines foster improvement in the design of agricultural machine engines (SCHLOSSER et al., 2020) and the development of exhaust gas post-treatment technologies, improving atmospheric emission control (RESITOGLU et al., 2015; DALLMANN & SHAO, 2016). Because different engine power classes are responsible for different permissible emission levels, post-treatment

Table 1 - Characterization of the main pollutant emissions from Diesel cycle engines.

Pollutants	Origin	Environmental Problems	Health Problems	Authors *
Carbon Monoxide (CO)	It results from incomplete combustion, where the oxidation process does not occur completely.	Air pollution.	Heart disease, choking, difficulty concentrating, slow reflexes, nausea, respiratory disease.	I, II, III
Hydrocarbons (HC)	As a result of low temperature that occurs close to the cylinder wall and uneven operating conditions.	They are precursors for the formation of tropospheric ozone, contributing to the realization of the greenhouse effect.	Respiratory diseases, cancer.	II, IV
Particulate Matter (PM)	It is produced by incompletely burning HC in fuel and lubricating oil.	Pollution of air, water, and soil, global climate change.	Premature death, asthma, lung cancer, cardiovascular disease.	II, V, VI
Nitrogen Oxides (NO_X)	High temperatures above 1600 °C in cylinders cause nitrogen to react with oxygen and influence its formation.	Acid rains, droughts, ozone depletion, terrestrial and aquatic ecosystems.	Lung irritation, lower resistance to respiratory infection, asthma, and bronchitis.	II, IV, VI, VII

Note: *Authors: I - (LEVY, 2015); II - (RESITOGLU, ALTINISIK & KESKIN, 2015); III - (RUFINO & COSTA, 2015); IV - (HICKEY et al., 2014); V - (LAWAL et al., 2016); VI - (KIM et al., 2017); and VII - (RESITOGLU & KESKIN, 2017).

system designs of engines can change significantly between power classes (DALLMANN & MENON, 2016) to satisfy the specifications of each standard, their respective stages, or both.

Strategies for reducing engine pollutant emissions can be divided into primary and secondary methods. Primary prevention measures include using alternative fuels instead of fossil fuels. Secondary measures include applying new technological approaches developed to control diesel engine pollutants (HICKEY et al., 2014; KUMAR et al., 2020). Engine pollutants can be controlled by introducing changes to engine cylinders and exhaust gas post-treatment devices (DALLMANN & MENON, 2016).

Cylinder mechanisms involve changes in engine design aimed at limiting pollutant emissions during fuel combustion. Emissions are controlled by developing modifications for fuel injection and air treatment systems or by introducing geometric changes to engines, which produce a homogeneous mixture of air and fuel (MÁRQUEZ, 2012; POSADA et al., 2016). However, in-cylinder strategies are insufficient for controlling NO_x and PM emissions (DALLMANN & MENON, 2016).

Therefore, post-treatment technologies are applied to develop potential emission control strategies (DALLMANN & SHAO, 2016). The main changes introduced into agricultural machinery in countries with strict emission legislation include a Selective Catalytic Reduction (SCR) for NO_x control, Exhaust Gas Recirculation (EGR) for decreasing NO_x emissions, and Diesel Particulate Filter (DPF) for controlling PM (MÁRQUEZ, 2012). The electronic fuel injection system significantly reduces gas emissions (KROGERUS et al., 2016). Fuel quality is another critical parameter because the sulfur content can affect the durability of post-treatment systems (POSADA et al., 2016).

Selective Catalytic Reduction (SCR)

The main sources of NO_x emissions worldwide are diesel engines. Currently, the SCR system is the best option to eliminate NO_x gas emissions (RESITOGLU & KESKIN, 2017). The system is characterized by transforming NO_x emissions into N_2 and water vapor (GUAN et al., 2014; LOVARELLI & BACENETTI, 2019). The chemical reactions for the process are changed using a catalyst to increase combustion efficiency with a urea–water solution (32% concentration) and exhaust gases (RESITOGLU et al., 2015). The ammonia (NH_3) mixture in urea, with the exhaust gases in the catalytic converter, activates chemical reactions of the pollutants and reduces NO_x emissions. For its safety and low toxicity, urea is the preferred selective reducing agent (Arla 32) for SCR applications (GUAN et al., 2014).

A disadvantage of this system is the need to equip the agricultural machine with a tank and a control module to inject the liquid-reducing agent into the exhaust duct (MÁRQUEZ, 2012). In addition to Arla 32, H_2, used as a NO_x-reducing agent, improves the conversion efficiency by decreasing the exhaust temperature. Both Arla 32 and H_2 should be stored in a suitable tank and not be mixed with the fuel (RESITOGLU & KESKIN, 2017). The SCR system may contain an evaluation mechanism known as on-board diagnostics, which detects the reducing agent and records failures caused by non-use.

Exhaust Gas Recirculation (EGR)

The EGR system is used to primarily control NO_x emissions. An advantage of this system is the utilization of the chassis space. Its operation is characterized by the recirculation of some exhaust gases in the engine through the EGR valve; these gases are mixed with the intake air (NAGARGOJE et al., 2016).

Exhaust gases are absorbed into the intake area by the cylinders such that the volume of the cylinder occupied by the gases cools the volume of oxygen in NO_x (HICKEY et al., 2014). With the decrease in oxygen, combustion occurs at low temperatures, reducing NO_x emissions. Pollutants are formed when an agricultural machine engine is subjected to high temperatures and pressures (THANGARAJA & KANNAN, 2016).

Diesel Particulate Filter (DPF)

The DPF post-treatment system is used to reduce PM emissions from diesel engine exhaust gases. The exhaust duct of the filter has walls consisting of a porous ceramic material. The process starts by blocking the alternating channels of PM to induce flow to the walls of the filter, resulting in pollutant retention (RESITOGLU et al., 2015). PM accumulation adversely affects engine performance and, if not controlled, causes abnormal functionality. If the back pressure is inadequate, the mixture of clean air with the fuel injected into the engine cylinders during combustion will be inadequate (HICKEY et al., 2014).

The filter features many parallel channels, which are typically square. The channel amplitude is influenced by its density. The filter walls must exhibit characteristics such as porosity. The DPF is sufficiently impermeable to PM and simultaneously permeable to other exhaust gases (RESITOGLU et al., 2015).

The excess soot accumulated in the filter negatively affects the operational function of the post-treatment system, mainly increasing fuel consumption and engine failures. The DPF must be regenerated by burning PM, which is held in its walls. PM can be burned using external sources, such as a flame-based burner, which oxidizes the pollutant in the filter until its soot load reaches an established limit, approximately 45% DPF pressure (RESITOGLU et al., 2015).

Alternative fuels

Biodiesel, natural gas, vegetable oil, ethanol, and mixtures of diesel oil with hydrated ethanol are alternatives currently developed for reducing human dependence on oil and its derivatives (ESTRADA et al., 2016; WEI & GENG, 2016; FARIAS et al., 2017; GENG et al., 2017). Alternative fuel technologies can be used to reduce pollutants and GHG emissions (GENG et al., 2017). Therefore, the demand for alternative fuels should increase, considering the steps adopted by society to ensure global energy security (MAHMUDUL et al., 2017).

Alternative fuels include a wide range of unconventional fuels, such as liquefied petroleum gas, coal-derived liquid fuels (coal-to-liquid), H_2, and natural gas (green fuel) (WEI & GENG, 2016; BAE & KIM, 2017). According to BAE & KIM (2017), the importance of using alternative fuels can be attributed to three factors:

I) Advancing energy sustainability, through the widespread utilization of alternative fuels derived from renewable energy sources, indicating efforts to limit energy from fossil fuels;

II) Improving engine efficiency and emissions owing to the superior physical and chemical properties of alternative fuels compared to those of conventional fuels;

III) Improving the unbalanced use of conventional petroleum-based fossil fuels.

Among alternative fuels, biodiesel can substitute mineral diesel oil in different fields such as light vehicles, heavy vehicles, agricultural machinery, and the maritime and aviation sectors (MAHMUDUL et al., 2017; ONG et al., 2021). The main difference between fossil fuels and biodiesel is the oxygen content (GENG et al., 2017). Biodiesel is produced from regenerative materials. Achieving the best energy properties with mineral diesel oil requires producing biodiesel to select suitable raw materials for its optimal performance (GENG et al., 2017; SHAMEER et al., 2017; ONG et al., 2021).

For example, soybean (*Glycine max.*) is traditionally used in Brazil as a raw material for biodiesel production (AVINASH et al., 2014). According to the Brazilian Energy Research Office (Empresa de Pesquisa Energética – EPE), soybean oil accounted for 69.2% of the main raw material for biodiesel and 17% for beef tallow in 2014 (EPE, 2015). In addition, other raw materials such as sunflower, corn, peanut, used cooking oil, wheat, beetroot, and animal fats, for example, lard and tallow, are used for fuel production (ALPTEKIN et al., 2015; MAHMUDUL et al., 2017; SHAMEER et al., 2017).

In internal combustion diesel engines, the biodiesel behavior depends on the selected materials (BAE & KIM, 2017). Their mixtures influence engine power and fuel consumption (FARIAS et al., 2017). The most critical factor influencing fuel consumption by agricultural machinery is the significant reduction of harmful emissions, such as PM, HC, and CO. However, NO_x emissions may increase (MAHMUDUL et al., 2017). Thus, biodiesel plays a crucial role in reducing the fossil energy demand, considering its availability, and it has ecofriendly properties. For these reasons, biodiesel is one of the main alternative fuels that should be used in different countries (ONG et al., 2021) to sustain the world's energy potential and achieve COP21 goals (AVINASH et al., 2014; EPE, 2015; ONU, 2015; MAHMUDUL et al., 2017).

Another proposed alternative fuel is hydrated ethanol added to mineral diesel oil (ESTRADA et al., 2016). The mixture of alcohols, such as ethanol, in fossil fuels, significantly reduces PM, HC, and NO_x emissions from internal combustion diesel engines because of their low carbon number (MOFIJUR et al., 2015; GENG et al., 2017).

Diesel engine emissions depend on the concentrations of the ethanol mixtures (YILMAZ, 2012). Studies have shown that mixtures with up to 3% hydrated ethanol added to mineral diesel oil can be a sustainable alternative fuel in agricultural tractors (ESTRADA et al., 2016). However, the high cost of manufacturing alternative fuels, such as ethanol and biodiesel, compared with that of petroleum-derived fuels, attenuates their production (BAE & KIM, 2017).

Figure 2 shows the systematization of the control of agricultural machine pollutant emissions. The processes (problems, strategies, and guidelines)

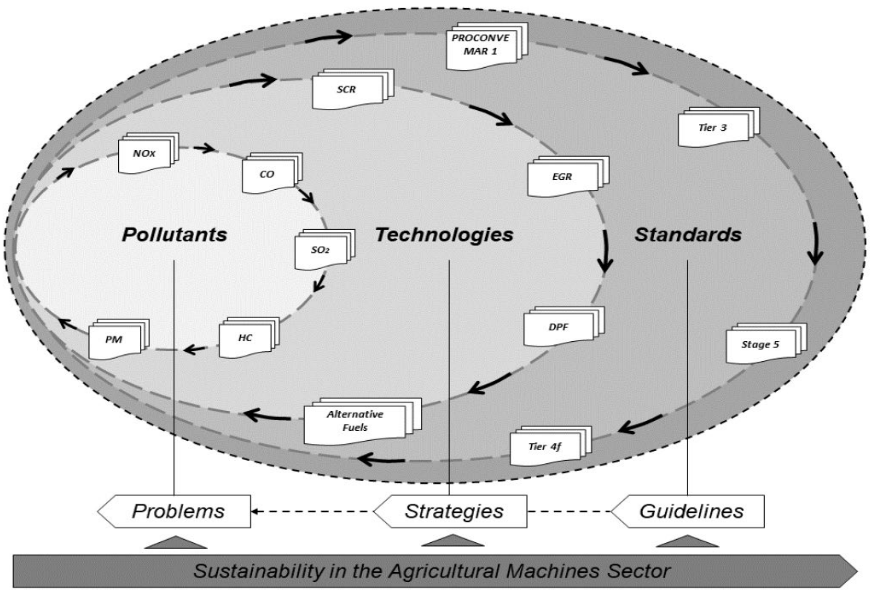

Figure 2 - Systematization of the control of pollutant emissions from agricultural machinery.

Note: Pollutants - Carbon Monoxide (CO), Sulfur Dioxide (SO2), Hydrocarbons (HC), Particulate Matter (PM), Nitrogen Oxides (NOX). Technologies - Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR), e Diesel Particulate Filter (DPF). Standards - Brazil (PROCONVE MAR 1), Japan (Tier 3), European Union (Stage 5), Canada and South Korea (Tier 4f).

are interdependent, and independent because each process directly influences the sustainability of the agricultural machinery sector. Each process comprises an element (pollutants, technologies, and standards) formed by a set of mechanisms, which can foster or barrier the transition from traditional to sustainable agriculture (DA SILVEIRA et al., 2021). The links between the processes and elements (Figure 2) require well-structured planning for a scale-up to the level of countries that can mitigate GHG emissions and increase climate resilience in the agricultural machinery sector.

CONCLUSION

This study clarifies sustainable development in the agricultural machinery sector based on data on diesel engine GHG emissions, bridging the gap in strategies and technologies for atmospheric pollutant control. These technological alternatives (SCR, EGR, and DPF), in addition to alternative fuels, aim at mitigating GHG emissions in agriculture. The information gathered in this review will help stakeholders achieve the successful development of sustainability in the agricultural sector. Further studies should be conducted to examine the state of the art of current regulations on agricultural machinery pollutant emissions in emerging countries, such as Brazil.

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DECLARATION OF CONFLICT OF INTERESTS

We have no conflict of interest to declare.

AUTHOR'S CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript.

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