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Research Article

AGRICULTURAL MECHANIZATION AND ITS ENERGY-EMISSION FOOTPRINT: A SYSTEMATIC PERSPECTIVE

Abubakar Sadiq Musa
Department of Agricultural and Bio-Environmental Resources Engineering, Faculty of Engineering, Federal University Dutsin-Ma, Katsina State, Nigeria
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Abstract

The growing dependence on fossil fuels in the agriculture sector—particularly through the use of mechanized farm equipment—has contributed significantly to global carbon dioxide (CO_2) emissions, compounding climate change concerns and challenging the sustainability of food production systems. This review critically examines the key contributors to carbon emissions in agricultural mechanization and evaluates technological maturity in relation to energy use patterns and fuel consumption in conventional farming practices.

The study aims to provide a structured roadmap for decarbonizing the agricultural supply chain, emphasizing how a transition to renewable energy technologies (RETs) and energy-efficient machinery can reduce the environmental impact of farm operations. By analyzing current frameworks and predictive models, the research identifies strategies to align agricultural machinery with renewable energy sources while considering the dynamic load demands of agrarian activities.

Rather than prescribing a single solution, the review advocates for a diversified approach that leverages all viable options—technological, operational, and policy-based—tailored to the specific capacities and contexts of farmers. It argues that meaningful CO_2 mitigation in agriculture is achievable through a combination of renewable energy integration, mechanization efficiency improvements, and sustainable fuel alternatives.

Furthermore, the manuscript highlights that significant CO_2 reductions are possible when decarbonization strategies are embedded across the entire mechanization process—from land preparation to harvesting. It calls for policymakers, practitioners, and agricultural stakeholders to adopt comprehensive energy transition strategies that are economically feasible, environmentally sound, and practically adaptable to varying agricultural systems.

In conclusion, this study offers an evidence-based foundation for rethinking energy consumption in agricultural production and presents actionable insights toward achieving sustainable, low-carbon farming systems without compromising food security or economic growth.

Keywords: Agricultural Machinery, Carbon Emissions, Energy Consumption, Sustainable Agriculture

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Introduction

Agriculture plays a vital role in the economy of all nations. Agricultural policies are intended not only for agricultural production in sufficient amounts and excellence but also for the fortification of the environment and the economic maturity of rural regions. Agricultural production is tightly related to the economy, environment, and energy consumption. Thus, it interrelates with all policies in these zones. In recent years, the adoption of machinery has increased in some regions of the world. In Brazil, for example, agricultural machinery production increased by 23.8% from 2017 to 2018, with approximately 66,000 units of tractors, combine harvesters, cultivators, and sugarcane harvesters (ANFAVEA, 2019).

As agriculture has modernized, mechanization has saved time for the productive process at all stages, from soil tillage to harvesting, especially in large-scale production. Agricultural modernization increases profitability and energy demand, water use and other inputs, and greenhouse gas emissions (Keyes et al., 2015). Universally, energy use is predicted to upsurge suggestively in the approaching years, with an extensive impact on the economy and the agricultural sector. This theme divulges the significance of research and development studies to advance more energy-efficient technologies in agricultural production. Energy efficiency is the ambition of energy to lessen the extent of energy entailed in offering products and amenities. In agricultural production, solar energy is not merely used efficiently in photosynthesis. Still, energy is also used nonstop as fuel or electricity and indirectly due to energy utilization in the production practices of agricultural machinery, as in Figure 1, fertilizers or pesticides.

Fig.1

Conceptual Framework

Increased demand for inputs through production processes threatens sustainability, making ecosystems vulnerable (Jãgerskog et al., 2014), primarily due to the possibility of water pollution and emission of greenhouse gases (Keyes et al., 2015). According to Dyer and Desjardins (2006), the energy required for the production of agricultural machinery is almost as high as the fossil fuel consumed during agricultural fieldwork.

Agricultural sustainability is advanced in many ways, focusing on economic, environmental, and social indicators individually or jointly (Lampridi et al., 2019). Nevertheless, a whole quantitative assessment necessitates time and struggle, which has frequently resulted in imperfect studies of environmental influence. To assess a production process, it is necessary to determine the material flows used in the product and those discharged as waste (Lampridi, Sorensen & Bochtis, 2020). Physical quantities of materials involved in production and their energy flows have been used to determine energy efficiency in several production processes (Andrea et al., 2016; Spekken et al., 2015). Materials required in combination with parameters such as embodied energy, carbon footprint, and water footprint can allow for a simplified assessment of the environmental burden of a particular product or production process (Mekonnen et al., 2018).

Voluminous scientific studies claim that the increasing share of carbon dioxide (CO_2) emissions as greenhouse gas (GHG) adds to global warming and climate change (IPCC Second Assessment on Climate Change, 1996). Population and sectorial economic growth are the key drivers of increasing energy demand and CO2 emissions in the agriculture sector (Raza and Tang, 2022). Because of the consumption of substantial fossil fuels, climate change impacts the climate, poverty, agriculture, income, biodiversity, and industrial income (Lin and Raza, 2019). In addition, fossil fuels and pollution-creating sectors have produced versatile issues, in which climate change has instigated a loss exceeding US$9.6 billion to the economy of Pakistan since 2010 (Pakistan CPEIR, 2017). The motive is that agriculture, manufacturing, and transport increase by 18.53%, 20.91%, and 13.04%, correspondingly, to the country's GDP (Pakistan Economic Survey, 2020).

Plentiful modus operandi is smeared to investigate the global impact of human conduct on earth. The hint of the carbon footprint results from the environmental footprint instituted in the 1990s. This measures the number of "earths" that are theoretically needed if individuals use earth resources at a similar level as the individual estimating their environmental footprint (Wackernagel and Rees, 1998).

After the industrial transformation, a considerable quantity of energy (coal, oil, and gas) has been widely utilized (Raza and Tang, 2022; Xiuhui and Raza, 2022). Fossil fuels give resilient power to economic development; hence, the extensive use of fossil fuels releases massive CO_2 emissions. The modernization of the agriculture industry produced a speedy rise in CO_2 emissions in this sector. Thus, analyzing the key factors saddling the agriculture sectors' CO2 emissions is obligatory to alleviate their ecological effect. However, the world's rapid population growth in current times will provide nominal growth in daily consumption (food) demand in the future. This rising demand for food will drive the growth of CO_2 emissions from the agriculture sectors (Jiang et al., 2021), further worsening global climate change. In addition, regarding agriculture, climate change, production, and energy consumption, Rehman et al. (2020) analyzed the pollution emissions of China's agriculture sector. They found that CO_2 emissions and GHGs have a positive relationship in the long run. Chandio et al. (2020)

investigated the effects of agricultural output on different regions of the world from 1982 to 2014. They found that agricultural land, energy, crops, and fertilizers positively affect CO_2 emissions.

Rehman et al. (2021a) investigated sectorial energy consumption for Pakistan and the agriculture sector from 1980–2016 and discovered a long-run relationship between agriculture energy consumption and economic growth. Dagar et al. (2021) examined India's technical efficiency of farmers with dissimilar volumes across agro-climate zones using a field survey method. They found that technical inefficiency with family and hired labour shows about 70% of average farmers are inefficient. Similarly, Rehman et al. (2021b) examined the impact of CO_2 emissions on forestry, crops, and livestock production from 1970–2017 in Pakistan. They discovered that all the factors positively correlate with CO_2 emissions in the short run. Subsequently, the outcomes of food crops on climate change cannot be unappreciated, which plays a vast part in spreading pollution (Boehm et al., 2018). About 19%–29% of GHGs of food production and land-freshwater mining adds 70% and employs 1/3rd of ice-free land worldwide (Aleksandrowicz et al., 2019). In addition to (Aleksandrowicz et al., 2019), the food system will give 60% of the rising population needs by 2050, thus fronting similar challenges, and food production might face massive pressure from environmental change.

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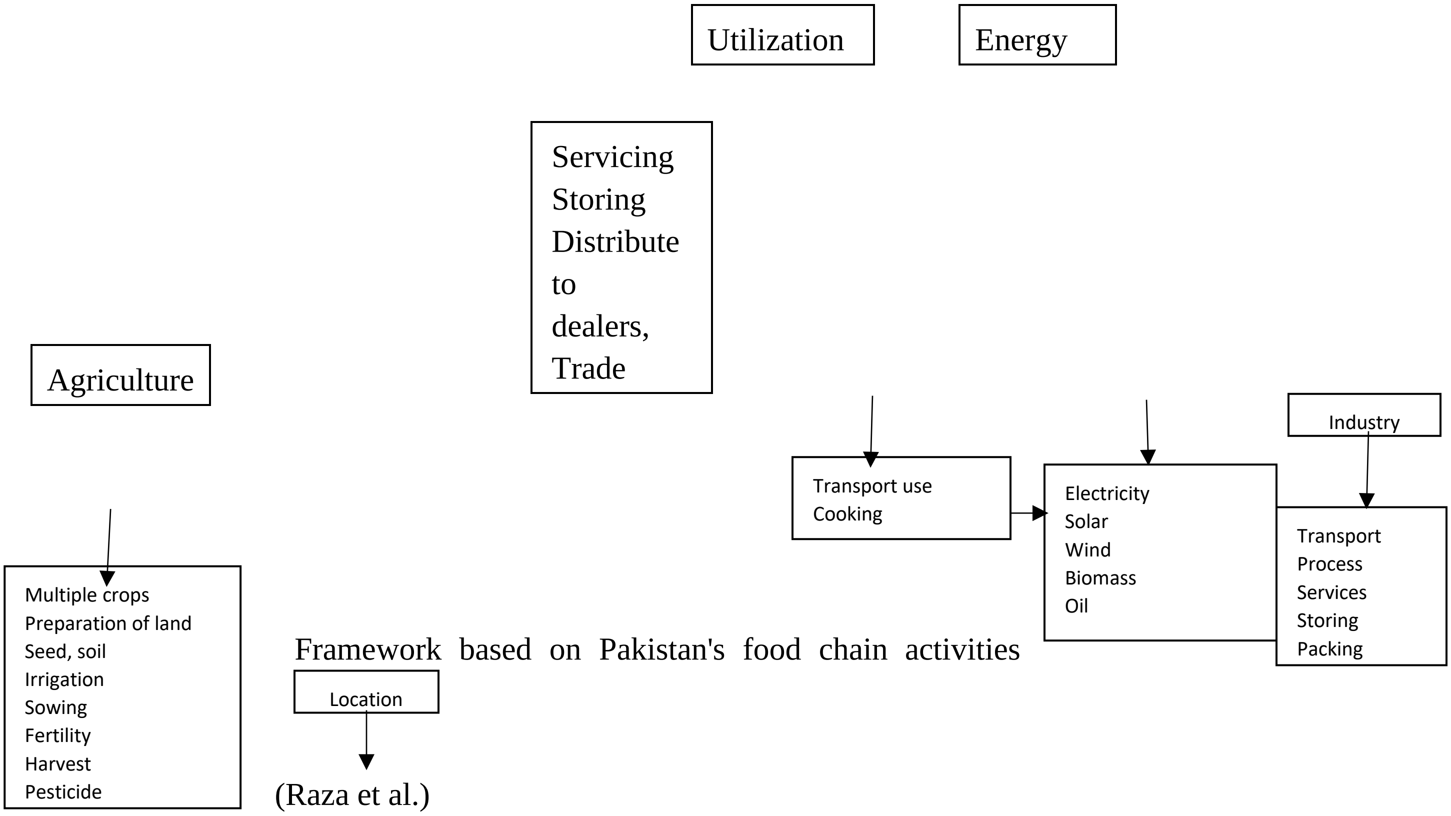

Framework based on Pakistan's food chain activities

(Raza et al.)

Thus, as stated by (Raza et al., 2023), the motivation and uniqueness of the current study are as follows: i) global agriculture CO_2 emissions and energy consumption have grown significantly during the current decades, and an annual growth of 6% is being experienced during the current decade (Carroll et al.,2018). Development and fuel consumption, the pollution factor is found; ii) the study investigates the most polluting activities, including human, faring, and related machinery, and gives a framework for decarbonizing the food supply chain. For this, the study suggests RETs for carbon mitigation and renewable energy sources with proper agrarian load; and iii) behind the economic impact, agriculture development and its contribution to the research and development provide an empirical analysis of free trade1 agreements and climate change agreements on environmental pollution. Moreover, ecological change lessens the elasticity and income of traditional farms (Lin and Raza, 2021).

The CO2 emissions of the agriculture detachment will grow significantly if the food supply system is not revised. The modern structure will offer a new context to ease or lessen the CO_2 emissions of agriculture production. Most of agriculture's production carbon footprint primarily comes from machinery, insecticide, and irrigation. As per Soofi et al. (2022), machinery significantly influences each farm's agricultural activity. Substituting machinery, i.e., tractors, harvesters, tube wells, other vehicles in farming, and insecticide processes with clean energy resources and renewable energy technologies (RETs) can mitigate the CO_2 emissions of agriculture.

Roadmap under prediction of technological maturity

Based on a critical works review on Pakistan and other countries, definitions and frameworks, the study measures the technical efficiency of agriculture productivity[3] employing these three major phases: preparation, technology and application inventory, and expert prediction of technology maturity phases. The critical technologies under the literature, for example, Rehman et al. (2021a) and Lin and Raza (2021), under Pakistan's agricultural development and technologies, are imperative to discuss from the preparation viewpoint. Phase II illustrates that the catalogues in the agriculture sector include the natural events and industrial inventories for the short- and long-run life cycle. For instance, Sinisterra-Solís et al. (2023) investigated the life cycle inventories of Spanish agriculture and established that environmental scores are reliable with the literature. The technology impact is the only way to reduce costs, risk of deterioration, and damage to products. Phase III discusses the outcomes of the prototyping and inventory technologies, their repercussion, and experts' consistent relationship with the agriculture market. This process is the product that analyzes the maturity of specific technology and measures future developments. A roadmap for agriculture development is drawn to serve as a reference for the government and related industries' planning of development approaches.

Carbon Emissions in Conventional Agriculture

The "carbon footprint" and CO_2 emissions have broadly applied in today's discussion against the threat of global warming, which is also rooted in the language of "Ecological Footprint" (Wackernagel and Rees, 1998; Pottier, 2022). Ecological footprint theory has been widely applied in different ways (for example, productive biological functions, underestimating the actual situation, calculating the physical amount of natural capital over the long run) using the countrylevel parameters around the world (known as a traditional ecological footprint) (Shujian and Shigai, 2013; Wang et al., 2018; Yang and Yang, 2019). The carbon footprint reveals the degree of the exclusive overall quantity of CO_2 emissions directly and indirectly attributed to an activity or collected over the product life cycle, which is consistent with (Wiedmann and Minx, 2008).

They explored that this term could be employed if all the GHGs were considered instead of only CO_2 emissions. As a quantitative measure of GHG emissions from any activity, it supports carbon emissions management and alleviation. According to Pandey et al. (2011), the emissions source can be quantified by calculating GHG discharges, and CO_2 emissions mitigation parts can be highlighted. However, in the current study, the CO_2 emissions of every farming section are discussed.

Fig. 2

Methodology

Fuel Consumption in Agricultural Production

About $^{1}/_{3}$ of agriculture's energy consumption is used up on fuel. Production methods and expanse are very crucial issues for fuel consumption. Fuel consumption differs sandwiched between 500– 15,900 litres/year. Diesel consumption for dissimilar products differs in 60–120 litres/ha, depending on the processing amount. The number of transactions is very vital. (Handler and Nadlinger, 2012).

Amount of Fuel Consumed

Fuel consumption in agricultural production activities, spent by tractor and irrigation pump engines in the routine of tools and machinery;

- Diesel fuel utilization,
- Lubricant oil utilization and
- Total fuel (Diesel fuel + lubricant oil) utilization.

Diesel fuel and lubricant oil costs consumed per unit production area (ha) by the tractor engine used throughout agricultural production processes are appraised as the entire fuel consumption. $m_t = m_D + m_i$ [L/ha] (1)

Where: m_t – total fuel consumption (L/ha), m_D – Diesel fuel consumption (L/ha) and m_l – lubricating oil consumption (L/ha).

Fuel consumption is defined for each application in the production process, built on the equipment size and the power needed to operate. Diesel, gasoline, or electric motors can deliver power for agricultural applications. The type of engine used is specified as a machine variable. Fuel consumption (liter/hour, L/h) in gasoline and Diesel engines are defined as follows, depending on the power of the tractor or other engine used and the load value of the engine (ASAE, 2000):

$$m_D = (YTH) \times (NMG) \times (YKV) \times (TMY) \times (YKI) \quad [L/h] \qquad (2)$$

Where: m_D – hourly fuel consumption of tractor engine (L/h),
YTH – Fuel consumption rate (L/kW–h),
NMG – Maximum usable or rated motor power (kW),
YKV – Fuel usage efficiency (decimal), TMY – tractor or engine load (0–1) and YKI – Fuel usage index (decimal).

Fuel usage efficiency (YKV) is a decreasing factor that justifies the time used for turning and some slight adjustments where the engine is running at less than operating speed. As an average worth for fuel use efficiency (YKV), the value governed by adding 1.0 to the area efficiency can be considered. Thus, when the area efficiency specified for an application reduces, the fuel usage efficiency decreases. In the fuel use index (YKI), the time spent outside the definite operation is considered for conveying tools or machines to the agricultural production zone and for some schedules. It is typically considered 1.10 in the fuel usage index (YKI). Any operation's motor load (TMY) is governed by dividing the average power needed to operate by the maximum available power.

Fuel Consumption Rate

Fuel consumption rate (YTH) for diesel engines varies on engine load and throttle adjusting (ASABE, 2011):

$$YTH = GA\,(0.22 + 0.096 / TMY) \quad [L/kW\text{–}h] \qquad (3)$$

Where:
GA – Partial throttle setting factor and is determined as follows:

$$GA = 1 - (T - 1)\,(0.45\,TMY - 0.877) \qquad (4)$$

Where:
T – Throttle setting and its value ranges from 0.0 to 1.0.

For ease, the throttle adjustment is 50% greater than the engine load at 1.0 maximum. Hence, for engine loads greater than 0.66, the throttle is presumed to be at maximum. For gasoline engines, this affiliation is defined as follows:

$$YTH = GA\,(2,74\,(TMY) + 3,15 - 0,203\,\sqrt{(697\,(TMY))}) \quad [L/kW\text{–}h] \qquad (5)$$

Lubricant Oil Consumption

The hourly lubricant oil consumption of the tractor engine exhausted for agricultural production processes is governed based on the rated power of the tractor. For assessing the hourly lubricant oil consumption in Diesel tractor engines, the following linear equation based on engine-rated power (P_e) and stated in ASABE Standard D497.7 Section 3.4 (2011) is employed as the reference model.

$$m_l = 0.00059 \times P_e + 0.02169 \quad [L/h] \qquad (6)$$

By Cancante et al. (2017), using MINITAB 17.0™ data processing software, linear regression (LRA) and analysis of variance (ANOVA) and the coefficients specified in equation (6) were governed as follows.

$$m_l = 0.000239 \times P_e + 0.00989 \quad [L/h] \qquad (7)$$

Where: m_l – hourly lubricant oil consumption of the tractor engine (L/h) and P_e – the rated power of the tractor (kW).

The Pearson correlation coefficient for the variables in equation (7) was r=0.90 (p<0.05). The standard errors of the constant term and linear coefficient in the developed model are 1.50 10–3 L/h and 9.0 10–6 L/h kW, correspondingly.

Fuel Energy Consumption

The tractor and irrigation pump motors ingest the whole fuel energy consumption in the agricultural production processes in the use of tools and machinery;

- Energy consumption related to Diesel fuel consumption,
- Energy consumption related to lubricant oil consumption and
- Considered the total energy consumption for diesel fuel + lubricant oil consumption. The fuel energy consumption (EC_f, MJ/ha) of diesel fuel and lubricant oil consumed per unit production area (ha) by the tractor and irrigation pump engines used during agricultural production processes is determined as follows.

$$EC_f = EC_D + EC_l \quad [MJ/ha] \qquad (8)$$

Where:

EC_f – total fuel energy consumption (MJ/ha), EC_D – Diesel fuel energy consumption (MJ/ha) and EC_l – lubricant oil energy consumption (MJ/ha).

Diesel fuel energy consumption (EC_D, MJ/ha) per unit production area (ha) by the tractor and irrigation pump engines used during production operations is determined as follows.

$$EC_D = m_D + LHV_D \quad [MJ/ha] \qquad (9)$$

Where:

EC_D – Diesel fuel energy consumption (MJ/ha), m_D – Diesel fuel consumption (L/ha) and

LHV_D – the lower heating value of Diesel fuel (MJ/L).

The lower calorific value of Diesel fuel consumed during production operations in the field with agricultural tools and machinery is considered LHV_D = 37.1 MJ/L (IPCC, 1996).

Lubricant oil energy (EC_l, MJ/ha) per unit production area (ha) of lubricant oil consumption by tractor and irrigation pump engines used during production operations is determined as follows.

$EC_l = m_l + LHV_l$ [MJ/ha] (10)

Where:

EC_l – lubricant oil energy consumption (MJ/ha), m_l – lubricant oil consumption (L/ha) and

LHV_l – the lower heating value of lubricant oil (MJ/L).

The lower calorific value of lubricant oil consumed during production operations with agricultural tools and machinery is considered LHV_l = 38.2 MJ/L (IPCC, 1996).

Throughout the task of tractors and other engine–powered equipment, carbon (C) in the fuel is transformed into carbon dioxide (CO_2) discharged in the engine exhaust. The amount of CO_2 discharged is proportionate to the amount of fuel consumed. The conversion factor used is 2.637 kg CO_2–equivalent per liter of Diesel fuel consumed. Fuel consumption is verified during the performance of each application. The annual total amount of fuel used in the business is established by summing up the amount of fuel spent in all usages. This total value is then multiplied by the emission factor to determine the CO_2 emissions from fuel combustion.

In the process of agricultural production processes, carbon dioxide (CO2) emissions are used up during the use of tools and machinery;

- CO_2 emissions related to Diesel fuel consumption,
- CO_2 emissions related to lubricant oil consumption and
- The total CO_2 emissions are associated with the total fuel (Diesel fuel + lubricant oil) utilization.

Captivating into account the lubricant oil consumption rate of the tractor engine, CO_2 emissions related to lubricant oil consumption can also be computed. The fuel-based CO_2 emission calculation method suggested by the Intergovernmental Panel on Climate Change is considered in the estimates to determine the CO_2 emissions related to fuel use due to agricultural production (IPCC, 1996). The recommended method for estimating CO_2 emissions based on fuel consumption is summarized in equations (12) and (13).

The total CO_2 emission ($kgCO_2$/ha) correlated to the unit production area (ha) fuel consumption by the tools and machines used during agricultural production is as follows.

$CO_{2,t} = CO_{2,D} + CO_{2,l}$ [$kgCO_2$/ha] (11)

Where:

$CO_{2,t}$ – total CO_2 emissions related to fuel consumption ($kgCO_2$/ha), $CO_{2,D}$ – CO_2 emissions related to Diesel fuel consumption ($kgCO_2$/ha) and $CO_{2,l}$ – CO_2 emissions related to lubricant oil consumption ($kgCO_2$/ha).

The CO_2 emission ($CO_{2,D}$, $kgCO_2$/ha) related to Diesel fuel consumption per unit production area (ha) by agricultural tools and machinery used during production processes is determined as follows.

$CO_{2,D} = m_D \times LHV_D \times EF_D$ [$kgCO_2$/ha] (12)

Where:

$CO_{2,\ D}$ – emissions related to Diesel fuel consumption ($kgCO_2$/ha), m_D – Diesel consumption (L/ha),

LHV_D – the lower calorific value of Diesel fuel (37.1 MJ/L) and

EF_D – CO_2 emission factor for Diesel fuel (0.07401 $kgCO_2$/MJ).

The CO_2 emission ($CO_{2,l}$, $kgCO_2$/ha) related to the lubricant oil consumption per unit production area (ha) by the agricultural tools and machinery used during production processes is determined as follows.

$$CO_{2,l} = ml \times LHV_l \times EF_l \ [kgCO2/ha] \quad (13)$$

Where:

$CO_{2,l}$ – emissions related to lubricant oil consumption ($kgCO_2$/ha), m_l – lubricant oil consumption (L/ha),

LHV_l – the lower calorific value of lubricant oil (38.2 MJ/L) and EF_l – CO_2 emission factor for lubricant oil (0.07328 $kgCO_2$/MJ).

Conclusion

To reduce the global average temperature, increase it to well below 2°C, no half-hearted ways can be taken, and all sectors must meet strict reduction targets. This manuscript is neither soliciting for softer actions for agriculture nor does it pretend to recommend the best pathway. As an alternative, it appeals to energetically recommend the use of all available options within the production process and with thoughtfulness of the specific conditions and capabilities of each farmer and of the sector to attain the highest conceivable reduction. The climate is fluctuating, its consequences are becoming evident, and there is extensive scientific agreement that it is caused by human actions that generate more greenhouse gasses than oceans, and biomass can be confiscated.

Due to the characteristics of agricultural machinery and the job they have to accomplish, the agricultural machinery industry believes that internal combustion engines persist and endure a viable and fitting solution for the coming era to deliver on the CO_2 reduction targets. This necessitates the promotion, production, and practice of alternate fuels, whereas other technologies (e.g., electrification) come to maturity.

To reach the final goal of carbon neutrality or even carbon negative balance, there are numerous possibilities for the agricultural sector, including fleet use. Farmers should have a strong expression in any valuation and maintain the freedom of choice on which alternatives to use in the most fit and cost-effective technique.

Recommendation

Within agriculture, manifold potential CO2-lessening options subsist farmers in becoming more sustainable while improving farm productivity. As there is no such thing as one size matches all in agriculture, farmers should have a deep-seated voice in evaluating which solutions work on their farm. For the coming years, one appropriate remedy in agriculture is the internal combustion engine with alternative fuels. Moreover, for victory to be specific, there must be a pledge to support the implementation and optimal use of innovative technologies, digital transformation, technical training, and essential investments in production and storage structure. This must be treasured within a long-term policy.

Customs in which the improved use of the most appropriate machinery within the crop production process helps reduce CO_2 from fuel combustion

The goal is to trim the CO_2 footprint of fossil fuel combustion from agricultural machinery. We identify the Well-to-Wheels perception from the automotive segment, which considers the chain of CO_2 emitting processes when associating cars, energy sources, and correlated emissions. A consistent application for agriculture would refer not to the distance traveled but to the tones of crop produced and harvested.

To achieve the target of CO_2 objectivity, these points must be dealt with systematically.

- How can the enhanced use of the most appropriate machinery within the crop production practice help lower CO_2 from fuel combustion?
- What substitutes are accessible for traditional fossil fuels?
- What are the profits, and what are the trials?
- How can unconventional technologies provide supplementary aid to turn agricultural land into more efficient carbon sinks?

Alternatives for fossil fuels Electrification

Eyeballing the practical viewpoints linked to electrification, the following can be commented on:

- **Full battery electric:** moreover, there are concerns about cost and life cycle; the main dispute associated with batteries remains energy density and weight. Taking the example of a standard tractor, the traditional structure with a diesel engine requires a 400l energy store of fuel (9.8 kWh/l resulting in a total of 3920 kWh or 1670 kWh due to the 40-45% engine efficiency). For the complete electric variant, this energy is stored in the form of Li-Ion batteries (best values of the battery pack anticipated in 2025: midterm 0.2 to 0.25 kWh/ kg), resulting in a total of 2000 kWh due to the high battery efficiency, weighs 9-10 ton and takes 5000l in capacity and this to do the same 8 hours of work (Handler & Nadlinger, 2012, and ASAE, 2000).
- **Fuel-cell electric**: A substitute to battery-electric solutions are fuel cell-electric solutions based on hydrogen. Subject to the type of fuel cell, they demand clean hydrogen prepared from non-efficient electrolysis. In terms of sustainability, green hydrogen (made from (surplus) renewable energy) or blue hydrogen (made from fossil fuel with carbon capture) should be aimed.

Alternative fuels

A 2020 JEC inquiry concluded that overall, for the alternative fuels they examined, virtually all offer better Well-To-Wheel performance than conventional diesel when used in Internal Combustion Engines.

- **CNG/LNG (compressed or liquefied natural gas with the gas**): As for CNG, there is a vehicle storage limitation as 4 × more storage gap is needed for the same working hours, even if there are many applications where this is more constrained capacity is not a problem. Extended independence can be attained for open field work if extra storage is placed on the employee side or in front of the tractor to replace the ballast weights. LNG permits a 2.5x better volumetric energy storage vs. CNG but requires storage at low temperatures to retain methane in a liquid state. Heat gradually affects the tanks, which can instigate the LNG inside to evaporate and produce a substance known as Boil-Off Gas (BOG), which needs to be expelled. This is a storage setback, bearing in mind the periodic use of agricultural machinery.
- **Biomethane:** gaseous fuel made from agricultural biomass or the organic fraction of the community solid waste, such as biogas, which is then supplementary to biomethane. Nonetheless, it may also be manufactured from dual-use plants, double cropping areas, intercropping sources, or biomass of biodiversity-reserved regions, which do not harmfully affect food production capability.
- **On-farm produced alternative fuels (bio-methane, plant oil):** production can produce numerous business chances for farmers from the use as fertilizer of the digested biomass (rest product), direct heat and electricity production, to use in agricultural vehicles and for suckling of the gas grid with biomethane for other applications.
- **Synthetic fuels (also known as Power-to-X fuels or e-fuels**): Green electricity can be transformed into liquid fuels from hydrogen using an environment-friendly approach with chemical synthesis processes.
- **Clean Plant oil:** This oil can be produced straight on the farm whenever desired. With modifications, traditional engines could run on plant oil according to decided quality standards. It is for direct use as storing over long time intervals is tough. Nevertheless, the technology has confirmed that it works, and takeoff has been low due to technical constraints and missing standardized quality boundaries.

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