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Investigating Agricultural Tractor Performance at High Altitudes: Challenges and Solutions

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Abstract: This study investigates the performance challenges of the Massey Ferguson (MF) 385 2WD tractor in high-altitude regions like Mount Bamboutos, Cameroon, where reduced air density and oxygen availability impair engine efficiency, leading to a 20-40% reduction in tractive force. Through a comprehensive literature review, the study evaluates active (engine-focused) and passive (drivetrain-focused) solutions to enhance tractor performance, prioritizing cost-effectiveness, simplicity, and sustainability for smallholder farmers. Unsuitable solutions, such as turbocharging and engine replacement, are deemed impractical due to high costs and complexity. Promising solutions include optimizing fuel injection timing and quantity, modifying transmission and differential gear ratios, and adjusting tire size and pressure, which improve torque, traction, and fuel efficiency with minimal modifications. The findings recommend low-cost, passive drivetrain interventions supported by training and subsidies to enhance agricultural productivity and livelihoods in highland areas. These insights inform tractor design and mechanization strategies for similar mountainous regions globally.

Keywords: Agricultural Tractor, Performance, High Altitudes, Mount Bamboutos, Cameroon, Massey Ferguson(MF) 385.

1. Introduction

1.1. Background of the research

Agriculture drives economic growth and rural life in Cameroon, accounting for 20% of GDP and 60% of the workforce [1, 2]. Cameroon's diversified agro-ecological zones, from northern savannahs to lush coastal plains, enable cash crop and food staple cultivation. Cash crops like cocoa, tea, coffee, cotton, and palm oil account for 30% of Cameroon's foreign exchange gains and integrate the country into global value chains [3, 1]. Most of the domestic food supply comes from cassava, maize, tomatoes, plantains, and yams, ensuring nutritional security for millions. More than 90% of agricultural producers are smallholder farmers, demonstrating the sector's role in rural economies and poverty reduction. Agriculture also boosts trade, transportation, and agro-processing, enhancing economic resilience and diversification. PNDA and other agricultural modernization programs show the government's commitment to market accessibility and productivity. The industry creates inclusive wealth and socioeconomic stability in Cameroon by leveraging its agro-ecological potential. Agriculture is important to Cameroon's culture and economy. Food security is provided to over 80% of the population, reducing imports and making nutrition affordable [3]. Women comprise about 70% of the agricultural workforce and help with domestic food production and farm management, boosting their socioeconomic power in rural areas [4]. Cameroon's agricultural diversity, including over 200 crop types, makes it a source of genetic resources for global food sustainability [3]. The 2010 Agricultural Development Strategy prioritizes private sector investment and technical innovation to enhance productivity and align the sector with national development goals [2]. Agriculture promotes social cohesion and equitable development by empowering women, creating rural jobs, and maintaining culture. Cameroon's agricultural industry is vital to food sovereignty, economic growth, and sustainable development.

Cameroon's agricultural output, especially in the hills, faces many issues. The lack of effective mechanization, especially in high-altitude tractors, is the biggest obstacle to development in these areas [2]. Various factors create uneven agricultural production. They mostly vary by location or geography [3]. Land use on slopes affects soil erosion, water infiltration, and sedimentation, which affects vegetation. The gradient of the terrain may limit yield in higher degraded areas, where flow accumulation might affect yield depending on the season. Regional differences make Cameroon's topography difficult. Landscapes include deserts, mountains, tropical rainforests, coastal plains, plateaus, and highlands. The thin air and steep terrain of the Bamboutos mountains cause challenges in certain areas. Besides agriculture, the Bamboutos Mountains are known for their biodiversity. Some rare animal and plant species live in the highlands.

1.2. Climate, farming methods and agricultural practices

The western highlands ecological zone has dry and rainy seasons in a tropical humid climate. Cameroon's western highlands have multiple volcanic swells from the Atlantic Ocean in the southwest to the Adamawa plateau in the northeast. The average precipitation in this zone is 2000-3000mm, with an average temperature of 20˚C. Lateritic soils cover various plains and plateaus on the western high plateau. These volcanoes are Bamboutos, Kupe, and Oku. Mount Bamboutos' climate varies due to its elevation and topography. Mount Bamboutos' highest elevations over 2000 meters are quite chilly. Mid-elevations between 1600m and 2000m get lower rainfall of 1600mm to 1700mm and are quieter than higher elevations. The lower elevations of 1400m to 1600m are warmer and wetter than the other two, with annual rainfall topping 1800mm. Decadal anomalies show precipitation along the southern Bamboutos highland slopes decreased significantly between 1980 and 2009. Because they lacked the necessary weather equipment, local farmers relied on signals such as wind direction, color, cloud location, and sunlight intensity to analyze abnormal rainfall patterns. This local method revealed practical explanations for climate change, which has dramatically affected agricultural cultivation cycles in this area, pushing farmers to use traditional knowledge to adapt. [5] The shift in the agricultural landscape, along with shifts in market demands and economic conditions, has led farmers to diversify their crops to include a variety of cash crops such as coffee that can thrive in the ecological setting [6]. In the north, these volcanoes connect to the Oku Volcanic Field and span over 50 km northeast-southwest. 2600-meter-high peaks surround a 10 km-wide caldera. Humid climates above 2000 meters have yearly rainfall of 2500mm [7].

Agroforestry is reliable and useful to the population in the Bamboutos Mountains. Agroforestry systems ensure long-term land productivity and livelihood diversification. These trees' root systems and green foliage fix nitrogen, recycle nutrients, prevent erosion, and enrich the soil. They improve soil, reduce wind, and provide a variety of food. Mountain farmers, however, face extreme weather and soil conditions that shorten the producing season, increase labor costs, and require specialized gear due to the difficult terrain. Conventional gear and tools are less effective for hostile environments and cost more [8]. Cameroon's Bamboutos highlands face overgrazing, deforestation, and poor farming. The second-largest water supply in Cameroon comes from this mountain. It supplies one-third of Cameroon's Edea hydroelectric plant's water, but this is diminishing. In August 2018, the Cameroonian government launched a joint initiative with ERuDeF and ITF to restore Mount Bamboutos' ecosystem and rich biodiversity while protecting indigenous people's homes and daily activities. This program aims to repair 35000ha of damaged land by planting over 15 million agroforestry and tree species and teaching and empowering 30,000 people to manage these ecosystems [9]. Traditional farming approaches boost resilience but cripple adaptability. Farmers suffer from low populations and few markets [10]. Limited agricultural practices, resources, and equipment limit production and innovation. This forces most farmers to utilize manual tools for medieval agriculture, limiting productivity for personal use and market sales. Poor road construction limits the number of crops transported from fields to markets and prevents harm to produce [11].

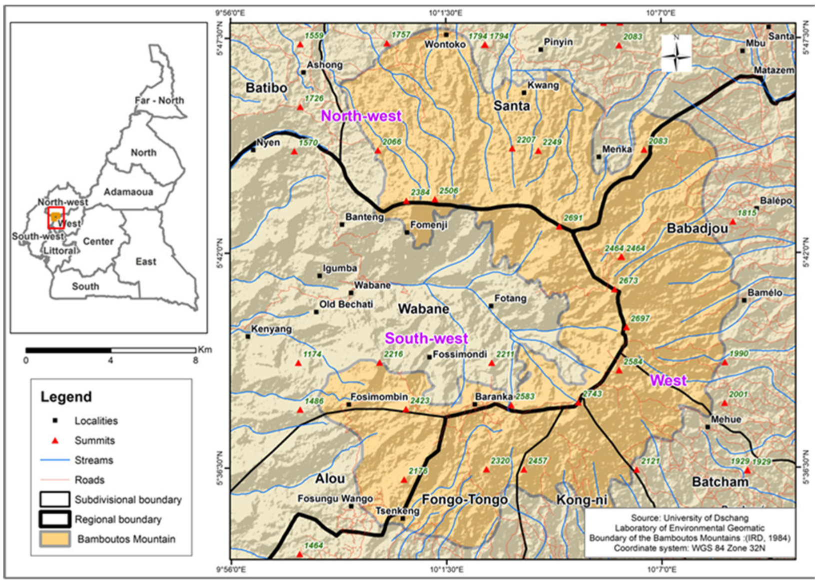

Figure 1. Mount Bamboutos map.

Source: Zanguim, G. H. T., Shidiki, A. A., Tientcheu, A. L. T., & Tchamba, M. N. (2022b). Analysis of the Spatio-Temporal dynamics of land use in the Bamboutos Mountains of the West region of Cameroon. *Open Journal of Forestry*, *12*(02), 216–234. https://doi.org/10.4236/ojf.2022.122012

2. Problem Statement

Increasing agricultural productivity in Cameroon requires mechanization, but high-altitude regions like Mount Bamboutos (2,740 meters) pose significant challenges. The Massey Ferguson (MF) 385 2WD tractor, powered by a naturally aspirated Perkins 4.236 diesel engine, is widely used in these areas but is designed for sea-level conditions. At high altitudes, reduced atmospheric pressure and air density decrease oxygen availability, impairing combustion efficiency. This increases brake-specific fuel consumption (BSFC) and reduces engine torque and power, particularly on Mount Bamboutos's steep, clay-heavy terrain. Consequently, the tractor's ability to plow, cultivate, or haul loaded trailers diminishes, slowing fieldwork and increasing operational costs for farmers with limited budgets. Limited quantitative data on the MF-385's performance degradation at high altitudes hinders the development of cost-effective solutions, perpetuating inefficiencies that affect agricultural output and livelihoods.

This study aims to review the literature for this problem and propose targeted solutions, such as turbocharging (engine-focused) or gear ratio adjustments (drivetrain-focused), to restore operational efficiency. By optimizing tractor performance, these solutions could reduce costs, increase work rates, and enhance profitability for smallholder farmers. Improved mechanization efficiency may also support local economies and food security in high-altitude regions. The findings will inform tractor design improvements and best practices for agricultural mechanization in similar mountainous areas worldwide.

Fig 2. Systematic Overview of Tractor Performance Challenges and Solutions at High Altitudes

3. Methodology

The methodology involves reviewing the literature to identify solutions for optimizing agricultural practices in high-altitude regions, evaluating their applicability to the study area, and proposing tailored solutions.

3.1. Solutions found from the Investigation of the literature

3.1.1. Boosting Engine Performance.

A more powerful diesel engine is one of the best ways to improve performance at high altitudes, as is Mount Bamboutos for the MF-385 2WD tractor. This approach rapidly compensates for high-altitude air density and oxygen shortages, which reduce engine combustion efficiency and brake torque [12]. High-performance engines boost power and torque under various conditions, including altitude. To promote fuel-air mixing and combustion, these engines have higher displacement, improved combustion chamber designs, and changed fuel injection systems. Increasing the tractor's engine power can increase its tractive force and operational capacity, decreasing the considerable decline in maximum tractive force in field soil and trailer operations [13]. Existing systems require the new engine to match the tractor's gearbox, chassis, and powertrain. Install the new engine with minimal alterations to save cost and structural damage. High-altitude engines with innovative air intake systems or naturally aspirated designs maintain good air-fuel ratios despite low oxygen [14]. While power production is vital, the engine should improve BSFC to counterbalance high-altitude fuel use. Engine durability and maintenance must be strong enough to run under difficult conditions with little maintenance. A higher-performance engine addresses altitude-induced brake torque loss to recover tractive force, allowing the tractor to perform effectively in field soil and road situations; Efficiency of fuel Optimising combustion efficiency in high-performance engines balances fuel consumption increases; Stronger engines allow tractors to manage heavier loads and steeper hills, boosting their agricultural usage [15]. Installation and system upgrades are included in engine replacement prices. Installing and integrating replacement components requires technical expertise; high-performance engines without emission controls may emit more [16] and harm the environment.

3.1.2. Engine Supercharging

After compressing and driving air into the engine with a turbocharger, the air-fuel mixture and density increase before entering the combustion chamber. More oxygen for burning restores power. This modification increases engine power and efficiency, making it popular in agriculture and industry. The primary tractor engine supercharging components. Turbochargers improve engine power and torque, which wastes gasoline and is terrible for ploughing. Optimising air-fuel ratio and reducing engine cycle pumping losses boost fuel economy [17]. Turbocharging saves gas. Turbocharged engines optimise air-fuel ratio and reduce pumping losses, making them more fuel efficient. Turbocharged engines have 10% lower BSFC and 30% higher torque and output than purely aspirated engines [18] [19]. Turbocharged engines perform better with intercoolers. Before entering the engine, intercoolers cool turbocharger-compressed air, increasing density and combustion efficiency. Cooler intake air increases power and reduces engine part thermal stress, extending their lifespan and reliability. Intercoolers regulate forced induction heat, allowing higher boost pressures without engine damage [20][21][22]. The application of supercharging is complicated. Turbochargers boost combustion temperatures, which can increase NOx emissions if unregulated. A turbocharger or intercooler retrofit requires technical expertise and may be expensive to install and integrate. Reduce boost pressure to minimise head gasket bursts and connecting rod damage [23][24]. Supercharging the engine enables MF-385 2WD farm tractors to overcome altitude performance drawbacks. Turbochargers increase air density and combustion efficiency at high altitudes, increasing power and fuel economy. An intercooler boosts performance and durability.

3.1.3. Modifying air intake systems

Lowering the air intake system's air density and oxygen levels at high elevations reduces diesel engine performance and efficiency. Adjusting the tractor's air intake system to boost airflow and combustion oxygen can decrease these effects. This adjustment optimises the air-fuel mixture to sustain engine performance in low-oxygen environments like Mount Bamboutos [25]. This solution requires high-altitude air filters. These filters maintain clean engine airflow despite low air density. Despite the thinner environment, high-altitude air filters let more air into the combustion chamber due to decreased airflow resistance. Advanced filtering technologies keep dust and debris from tractors' engines in dusty agricultural activities [26]. Beyond filters, changing the air intake system layout improves high-altitude engine performance. Larger air intake apertures increase airflow, compensating for reduced oxygen levels at higher elevations. Cold air intake systems extract colder, denser air outside the engine compartment to improve combustion and power production. Ram air intakes increase engine airflow, while variable shape intakes maintain performance at varying altitudes. Switching air intake systems has various advantages. Oxygen increases fuel combustion, increasing power production and reducing fuel use. In cold or rainy high-altitude situations, modified intakes must reduce ice and water intrusion [27].

3.1.4. Injection Timing Optimization

Diesel engine combustion in high-altitude environments like Mount Bamboutos requires injection timing optimisation. High altitudes' low air pressure and oxygen density delay ignition, burn inefficiently, and create pollution. Fuel combustion is optimised via injection time, improving engine performance and efficiency. The injection time is the exact moment fuel enters the combustion chamber relative to the piston. High altitudes reduce cylinder pressure and temperature, hindering fuel injection and combustion. If ignored, this delay can cause incomplete combustion. A proven solution is to advance injection timing by 1°–5° before TDC. Early compression stroke fuel injection improves air-fuel mixing and ignition, increasing combustion efficiency [28]. Many benefits come from optimised injection time. Lowing BSFC is vital because high-altitude operations increase. Second, it increases engine power by reducing brake torque loss at 2,740 meters. Third, it decreases high-altitude incomplete combustion smoke and CO. Be careful when advancing injection timing. Overprogression increases diesel knock, which causes cylinder pressure spikes and engine damage. Overly advanced timing lowers engine power at lower RPMs and raises peak cylinder temperatures and NOx emissions. For optimum results, make incremental, tractor-specific changes. Increasing injection timing by a few degrees improves combustion efficiency without diesel knock or engine wear. Speeding up air-fuel mixing and combustion brings peak pressure closer to TDC for maximum energy conversion and less ignite delay. Modern injection timing optimisation uses mechanical fuel injection pump improvements or barometric pressure sensor calibration. Altitude sensors adjust injection timing for performance at different heights. Smooth operation and pollution reduction are these systems' strengths.

3.1.5. Injected Fuel Quantity Optimization

Optimizing fuel injection into the combustion chamber is essential for diesel engines in high-altitude situations like Mount Bamboutos. Low air density and oxygen availability at high altitudes cause an air-fuel mixture mismatch, resulting in inefficient combustion, increased emissions, and lower engine power. Changing the fuel injection quantity helps balance the air-fuel ratio, improve combustion efficiency, and lower fuel consumption. Low intake air density reduces combustion oxygen at high elevations. To avoid an extremely rich mixture that can cause incomplete combustion, soot production, and CO emissions, the fuel quantity must be reduced. Optimizing the injected fuel quantity maintains a more uniform air-fuel combination, improving combustion efficiency and reducing soot and unburned hydrocarbons (HC) emissions [29].

Injecting gasoline precisely can improve engine performance parameters including BSFC and thermal efficiency. Studies suggest that improving fuel injection parameters can reduce BSFC by 5.9% at high altitudes and increase engine torque by 5.6%. By matching fuel injection to reduced oxygen levels, the cylinder can burn more completely and convert energy better [30]. The optimization method fine-tunes fuel injection factors, which can significantly convert energy better. Change injection time, pressure, and injector nozzle design to precisely meter fuel. For non-electronically controlled diesel engines like the MF-385 2WD tractor, fuel pump or injector settings can be adjusted mechanically for optimal results. Reducing injection volumes incrementally while monitoring engine performance characteristics can assist find the best power-to-fuel efficiency ratio [31]. However, optimizing injected fuel quantity is difficult. Lean mixes can cause misfires or limit engine output if fuel delivery is excessively reduced. Additionally, mechanically controlled fuel injection systems require calibration and knowledge to control precisely. Sensor-based real-time modifications in modern diesel engines with electronic control units (ECUs) optimize injected fuel volumes under different conditions. Optimizing injected fuel volumes has benefits beyond performance. Soot and NOx from inefficient combustion processes are reduced by this method, lowering exhaust emissions. It also reduces thermal stress on engine components from over fueling or inefficient combustion, improving reliability.

3.1.6. Change Used Fuel Properties

By changing its fuel characteristics, the MF-385 2WD tractor can perform better in high-altitude conditions like Mount Bamboutos. Inefficient combustion, fuel consumption, and emissions occur from high elevations' low air density and oxygen. Fuel additives or formulae can increase combustion efficiency and engine performance, and reduce the consequences of high-altitude combustion. The benefits of fuel additives include high-altitude combustion. Cetane improvers, oxygenates, and combustion catalysts improve fuel specs. Cetane improvers speed fuel ignition to ensure optimal combustion in low-oxygen conditions. Biodiesel and ethanol blends balance air-fuel ratios and reduce incomplete combustion by adding oxygen. Metallic combustion catalysts like ferrocene reduce combustion activation energy, allowing more fuel to burn and less smoke [32].

MF-385 2WD tractors without oecus can easily implement these changes. Fuel tank additives can be added at rates farmers allow. A modest percentage of biodiesel or oxygenated fuel mixtures improves combustion without engine modifications. Cetane improvers integrate easily and stabilise combustion duration at varied altitudes [33]. Benefits of fuel modification go beyond combustion efficiency. Fuel optimisation can help restore engine power lost to high-altitude low oxygen availability. Higher heights increase BSFC, which this approach reduces. Soot and CO emissions from incomplete combustion in low-oxygen settings are reduced [34]. However, this solution has limitations. Farmers in remote highlands may have problems procuring chemicals. Long-term additive use may wear seals or components in older engines like the MF-385 2WD. Due to oxygen supply limits at high altitudes, additives may not fully restore engine power to sea level. Fuel modification is cheaper than engine replacement or turbocharging. When done well, it's affordable and profitable. This procedure restores performance when combined with injection time adjustment and air intake system upgrades.

3.1.7. Compressed Air/Oxygen Tanks

At high altitudes like Mount Bamboutos, compressed or oxygen-enriched engine intake air can enhance oxygen availability. Insufficient oxygen for combustion causes power loss in the MF-385 2WD tractor's mechanically controlled, naturally aspirated diesel engine. Oxygen improves combustion efficiency, restoring engine brake torque and lowering BSFC at high altitudes. Portable oxygen and oxygen enrichment membranes can oxygenate engine air. Portable compressed oxygen tanks mix enriched air with ambient intake air using demand-based controls. Instead of compressed tanks, oxygen enrichment membranes separate nitrogen from input air to boost oxygen concentration by 26–28% at higher elevations. Membrane systems are ideal for isolated places since they save tank refilling and run constantly [35]. Compressed air or oxygen tanks help high-altitude tractor operations. It restores engine power by improving combustion efficiency and reducing low-oxygen ignition delays. This burns gasoline completely, reducing unburned hydrocarbons and soot and restoring field and road tractive force. Lowering BSFC improves fuel economy since altitude increases fuel consumption. Third, these systems work in highland cold without fuel gelling or intake icing. Benefits aside, this solution has downsides. Higher combustion temperatures from increased oxygen levels increase NOx emissions, a major concern. At 26% intake oxygen concentration, NOx emissions treble, requiring after-treatment devices not found in MF-385 tractors. Highlands may make portable compressed air system refills difficult. Membrane systems cost but last and require little maintenance. Consider compressed oxygen storage and handling safety.

This boosts performance when combined with injection timing or air intake adjustments. By delaying injection timing, higher oxygen levels enhance power without diesel knock. Under changing operating conditions, compressed air systems with altered intake designs provide consistent airflow for improved combustion.

3.1.8. New Transmission

An optimised gearbox system can passively fix the MF-385 2WD tractor's performance concerns at high altitudes like Mount Bamboutos. Engine brake torque drops from 28.78% to 30.32% at these levels, limiting tractor tractive power on field soil or towing trailers. Modern gearboxes with higher gear ratios use engine output more efficiently, improving traction and efficiency. Modern multi-speed gearboxes and CVTs outperform fixed-gear systems. CVTs' seamless gear ratio range helps tractors maintain engine RPM under different loads. This reduces manual gear shifting power losses and optimises engine performance in high-altitude circumstances. Transmissions like John Deere's e23™ PowerShift and ZF's TERRAMATIC® CVT improve fuel efficiency and torque delivery by regulating speed and power distribution [36]. The tractor needs a new gearbox with wider ratios for traction and torque multiplication at lower speeds on steep slopes and uneven terrain in the highlands. Smooth speed changes from properly spaced gears reduce engine and transmission strain and save power. This helps with ploughing and hauling heavy loads that require tractive effort. Transmission upgrades have benefits beyond tractive force. Better transmissions can lower engine RPM during light-load or transport operations, lowering BSFC at this altitude. Modern transmissions have hill-hold and automated downshifting, making steep climbs safer and easier [37]. New gearbox systems are complex to build. Small farmers on a budget may find gearbox replacement costly. An older tractor like the MF-385 may need extensive drivetrain and chassis modifications to retrofit a modern gearbox, increasing installation complexity and cost. Complex CVTs may require more maintenance than gearboxes. These constraints aside, a new gearbox is a long-term investment that can boost tractor performance at high elevations. Paired with passive measures like tyre size or differential gear ratio optimisation, increases traction and load-handling [38].

3.1.9. Changing Transmission

Changing gearbox gear ratios at high altitudes like Mount Bamboutos improves the MF-385 2WD tractor's performance cheaply. The tractor's engine brake torque diminishes substantially at these elevations, decreasing its tractive force and strength for heavy agricultural work. In rigorous field operations, gearbox gear ratios can be altered to enhance torque and pulling power to compensate for power loss [39]. One of the best ways to enhance wheel torque is to lower gear ratios. The engine's torque doubles at 4:1 gear ratio, making them ideal for ploughing or pulling heavy loads on steep slopes. This adjustment keeps the tractor moving with minimal engine power. Field gear ratio optimization improves drivetrain strain, traction, and operating economy [40]. Gearbox changes improve more than torque. Adjusting gear ratios enables the tractor run at lower engine speeds under minimal load, saving fuel. High altitudes boost BSFC from 6.71% to 9.08%. Smoother gear shifts extend gearbox system longevity [41]. Transmission system modifications are difficult. Gear set calibration or replacement requires technical expertise to assure tractor drivetrain and engine output compatibility. Extreme gear ratio decrease may impair maximum speed and road transport efficiency. Balance torque improvement and speed to optimise work performance. This method works well with passive tactics like tire size or differential gear ratio optimisation., wider tires and lower gearbox gear ratios improve traction and load-handling without slowing down. This approach and active methods like injection time manipulation can boost high-altitude performance [42].

3.1.10. Altering Differential and Final Drive Gear Ratios

The MF-385 2WD tractor's performance at Mount Bamboutos can be passively improved by changing the differential and final drive gear ratios. These heights reduce our tractor's tractive power and ability to undertake heavy agricultural work by 28.78% to 30.32%. To compensate for power loss, differential and final drive gear ratios can be altered to maximise wheel torque, traction, and efficiency. Differential and final drive are important tractor powertrain parts. These systems delay the engine and increase torque before driving the rear wheels. Adjusting gear ratios improves high-altitude performance. From 3:1 to 4.5:1, gear ratios increase torque multiplication, allowing the tractor to manage high loads, climb steep hills, and perform well on rough or muddy terrain. It optimises engine output since altitude-related power losses limit tractive force [43]. Changing differential and final drive gear ratios increases pulling power and traction. Lower gear ratios enhance torque at lower speeds, making them excellent for ploughing, trailering, and challenging field conditions. This adjustment lowers wheel slippage on uneven or sloppy conditions by improving wheel power distribution. An added benefit is fuel efficiency; optimising the powertrain for high-torque applications reduces engine effort for heavy workloads, offsetting the 6.71% to 9.08% BSFC gain at high altitudes. Smoother torque delivery reduces drivetrain component strain, extending lifespan and lowering maintenance costs [44]. Differential and final drive gear ratio. changes are challenging. Crown pinion gears and planetary gears require technical expertise to replace or adjust. Lower gear ratios improve torque but decrease speed, reducing road transport efficiency. Torque improvements and speed must be balanced for workload optimisation. This tactic complements other performance-boosting methods. Tire size and gear ratio optimisation can increase traction and load-handling without impacting speed. This method can improve altitude performance with active solutions like injection time optimisation or air intake adjustments [45].

3.1.11. Tire Size Change

The MF-385 2WD tractor's tire size can be passively altered to address high-altitude performance difficulties like Mount Bamboutos. Engine brake torque diminishes at 2,740 meters, limiting tractive power, especially for heavy farming. Altitude-related power loss can be corrected by changing tyre size to improve grip, reduce slippage, and increase the tractor's power gearbox. In challenging situations, larger tires perform better. Larger tires have more ground contact, enhancing grip and reducing slippage. Ploughing and trailering demand strong pulls. This is vital. Wider tires properly distribute weight, reducing soil compaction and improving float on soft or wet terrain. These benefits protect performance and decrease field production disruptions from low traction or soil disturbance [46]. Fuel efficiency is another benefit of larger tires. Wider tires minimise rolling resistance and slippage, boosting tractor economy and lowering high-altitude BSFC. Larger tires even out ground forces, decreasing drivetrain wear. It extends tyre life and lowers maintenance costs. To maintain tractor design and function, changing tyre size requires careful consideration of several factors. Tractor gearbox or differential gear ratio modifications may be needed to balance speed and torque as the tyre diameter increases. Tractor fenders and mudguards may need to be adjusted for larger tires. Tire size alterations must not affect the tractor's stability or center of gravity on slopes [47]. This tactic complements other performance-boosting methods. High air pressure and larger tires reduce soil compaction and improve grip and flotation. This method maximises tractor traction without compromising speed or efficiency using gearbox or differential gear ratio modifications [48].

3.1.12. Tire Air Pressure Optimization

Optimizing tire air pressure improves the performance of the MF-385 2WD tractor at high altitudes like Mount Bamboutos. At 2,740 meters, engine brake torque drops 28.78% to 30.32% and fuel consumption rises 6.71% to 9.08%, reducing operational efficiency. Farmers in rugged highland terrain can improve traction, rolling resistance, and fuel economy by adjusting tire pressure.

Low-density air at high elevations hinders tire contact. Lowering tire pressure enhances the tire's footprint on the dirt, boosting traction. This helps with heavy-duty field tasks like plowing and trailering [49]. Improved traction reduces slippage, transferring more engine power to the ground. Optimizing tire pressure improves traction and minimizes rolling resistance. Proper tire pressure reduces energy losses from tire deformation and soil compaction. This reduction in rolling resistance reduces high-altitude fuel use, improving fuel economy and lowering operating expenses.

Adjusting tire pressure needs careful consideration of numerous aspects to minimize unwanted effects. Too low tire pressure can overheat and prematurely wear tires, while too high pressure will limit traction and soil compaction, lowering agricultural output [50]. Tires should be inflated to their manufacturer-recommended pressures based on load and operating conditions to balance these extremes. Advanced technologies like central tire inflation systems (CTIS) allow farmers to regulate tire pressures for field and road performance dynamically. This technique works best with other strategies, like tire size or drivetrain modifications. Optimizing air pressure and using larger tires can improve grip and flotation on soft terrain while reducing soil damage. This method and differential gear ratio modifications allow the tractor to maximize its traction without sacrificing speed or efficiency [51].

3.2. Solutions for the Massey Ferguson (MF) 385 2WD Agricultural Tractor

Based on the constraints and solutions discussed in the previous section, four categories of solutions were identified: unsuitable options, solutions with potential adverse effects requiring caution, solutions offering limited improvements, and solutions with high potential for significant gains.

3.2.1. Unsuitable Solutions

Installing a higher-performance engine significantly boosts tractor power but is prohibitively expensive and requires extensive modifications to the chassis and drivetrain. Similarly, adding a turbocharger enhances engine output by increasing air intake but increases costs, necessitates intercoolers and modified intake systems, and demands more frequent maintenance, which is impractical for smallholder farmers. Using compressed air or oxygen tanks to enrich intake air is infeasible due to their limited capacity (e.g., only minutes of operation per tank), added weight, and reliance on external refilling stations unavailable in remote areas. Replacing the transmission system improves performance but involves high costs and significant structural changes, making it unsuitable for most farmers in Mount Bamboutos's region [13].

3.2.2. Solutions with Potential Adverse Effects (Require Caution)

Adding combustion-enhancing fuel additives can increase engine power but risks corroding fuel system components, accelerating wear on injectors and pumps, and causing vapor lock, especially in high-altitude conditions. Similarly, increasing rear tire size moderately improves traction but, if oversized, may increase rolling resistance, reduce stability, and heighten tipping risks on Mount Bamboutos's steep, uneven terrain [52].

3.2.3. Solutions with Limited Improvement Potential:

Modifying air intake systems can improve the engine's volumetric efficiency to some extent; however, the benefits are generally marginal because the fundamental limitation of reduced air density at high altitudes persists. Adjusting injection timing by advancing it within a range of 3 to 5 crank angle degrees helps minimize combustion inefficiencies associated with altitude-induced oxygen deficits. Yet, this adjustment typically yields only minimal improvements in overall engine power. Similarly, optimizing tire pressure may provide slight performance enhancements, but these gains are often limited and do not significantly surpass the effectiveness of maintaining standard, manufacturer-recommended pressure settings [53].

3.2.4. Solutions with High Improvement Potential

Optimizing the fuel injection quantity can increase engine power and torque by delivering more fuel to the combustion chamber; however, this often comes at the cost of reduced fuel efficiency and increased emissions. The primary objective of this approach is to balance enhanced performance with minimal penalties to fuel economy. Modifying the transmission gear ratio, particularly within the epicyclic unit, provides an effective means to compensate for torque loss in low gears without compromising the tractor's performance at higher gears or its maximum speed. In contrast, adjusting the differential and final drive gear ratios boosts torque output across all gears but results in a reduced overall speed range, including a lowered top speed, thereby affecting the tractor's transport efficiency [54].

4. Results & Discussion

Solutions were categorized into active (engine-focused) and passive (drivetrain-focused) approaches. Active solutions, tailored for the MF-385's mechanically controlled Perkins 4.236 diesel engine, include modifying fuel injection quantity, advancing injection timing, and improving air intake systems. Passive solutions include adjusting transmission, differential, or final drive gear ratios, optimizing tire pressure, and increasing tire size. Unsuitable solutions like turbocharging, higher-performance engines, and compressed air tanks were excluded due to cost and complexity.

To select solutions for implementation, three guidelines were established: (1) cost-effectiveness, prioritizing minimal development and implementation costs for smallholder farmers with limited resources; (2) simplicity, ensuring solutions are easy to understand, teach, and apply given farmers limited technical training; and (3) sustainability, requiring durable solutions with minimal maintenance and no reliance on specialized, locally unavailable components.

Based on these criteria, promising solutions include optimizing fuel injection quantity, advancing injection timing, modifying transmission and final drive gear ratios, and adjusting tire size and pressure. These will be discussed in detail in the following sections

4.1. Active (Engine-Focused)

4.1.1. Injection Timing Optimization

Optimizing injection timing is essential for improving the combustion performance of diesel engines in high-altitude conditions, such as those found in the Mount Bamboutos region. At elevations around 2,740 meters, the atmospheric and oxygen partial pressures are significantly reduced, leading to delayed ignition timing and decreased combustion efficiency. To counter these effects, advancing the injection timing by approximately 1° to 5° before top dead center (TDC) has enhanced combustion phasing and minimized ignition delay. Earlier injection allows for better air-fuel mixing in the lower ambient pressure, increasing thermal efficiency and reducing BSFC. Furthermore, optimized timing recovers some of the engine's brake torque loss, which is crucial for maintaining tractive force during field operations [55].

However, the degree of timing advance must be carefully calibrated. Excessive advancement may lead to diesel knock, increased mechanical stress, and elevated nitrogen oxide (NOx) emissions due to premature combustion. Therefore, mechanical timing adjustments or barometric pressure sensors with altitude compensation may be used to fine-tune the injection parameters according to ambient conditions. Overall, injection timing optimization offers a low-cost, moderately effective means of restoring engine responsiveness in highland environments [56].

4.1.2. Air Intake Modifications

Modifying the air intake system offers another effective strategy for improving engine performance at high altitudes by tackling the challenge of decreased oxygen availability. To address this, several intake modifications can be implemented. Firstly, high-altitude-specific air filters, designed with low-flow resistance to optimize airflow into the combustion chamber, can be utilized [57]. These filters also feature upgraded particulate filtration materials to safeguard the engine in dusty agricultural environments. Secondly, cold air intake systems can be installed to pull in cooler, denser air from outside the engine bay, enhancing oxygen concentration and combustion efficiency. Additionally, ram-air intakes and variable geometry intake manifolds can fine-tune airflow across various speeds and load conditions, ensuring more consistent engine performance despite atmospheric challenges. While the benefits of intake modifications are generally modest due to the inherent limitations of ambient air pressure, these changes improve fuel-air mixing, lower particulate emissions, and provide slight enhancements in brake torque and engine stability. Furthermore, they are relatively straightforward to implement and necessitate minimal structural alterations, making them an attractive option for smallholder farmers [58].

4.2. Passive (Drivetrain/Tire-Focused):

4.2.1. Gear Ratio Adjustments (Transmission and Differential)

Passive modifications to the drivetrain, especially through adjustments to the gear ratios in the transmission and differential systems, represent a practical approach to compensate for the power loss experienced by agricultural tractors operating at high altitudes. As demonstrated in the Mount Bamboutos case, engine brake torque can decrease by approximately 28% to 30% due to reduced air density, leading to a corresponding drop in tractive force and operational capability in challenging terrains [59].

Adjusting gear ratios allows the tractor to make the most of the available engine torque by increasing the torque multiplication delivered to the wheels. Lowering gear ratios within the transmission system specifically amplifies torque output at the expense of vehicle speed, enabling the tractor to maintain sufficient pulling power under heavy load conditions like plowing or hauling. This advantage is especially valuable in field operations where high torque at low speeds is crucial. Additionally, modifying the differential and final drive gear ratios can improve torque transfer efficiency to the rear wheels, enhancing traction on slippery or uneven surfaces. For example, increasing the differential gear ratio from 3:1 to 4.5:1 results in greater torque multiplication, facilitating better load-handling and hill-climbing performance in low-oxygen, high-altitude environments. Such modifications reduce wheel slip and mechanical strain, boosting operational efficiency and extending component lifespan [60].

Although modifying gear ratios can effectively restore tractive power, it introduces trade-offs, such as reduced maximum travel speed, which may affect road transportation efficiency. Furthermore, these adjustments require precise mechanical expertise to ensure compatibility with the existing powertrain and to avoid excessive drivetrain stress. Overall, optimizing gear ratios is a cost-effective and practical passive solution for enhancing high-altitude tractor performance. When combined with active engine-focused strategies, such as optimizing injection timing and improving air intake, these drivetrain adjustments significantly restore operation.

4.2.2. Tire Size and Air Pressure Optimization.

Optimizing tire size and air pressure are crucial passive measures for enhancing tractor performance in high-altitude environments, where engine power is inherently reduced due to lower atmospheric oxygen levels [61]. The reduction in engine brake torque, along with challenging terrain features like uneven ground and soft soils found in areas such as Mount Bamboutos, requires improvements in traction and minimizes energy losses at the ground-vehicle interface. Increasing tire size, especially in tire diameter and width, effectively expands the rolling circumference and contact area, thus boosting traction and decreasing wheel slip during heavy-duty agricultural tasks. Larger tires spread the vehicle load over a wider surface area, which reduces soil compaction and improves flotation on soft or moist soils, helping to maintain soil structure and productivity. This enhanced grip allows for better transmission of the reduced engine torque to the field, partially compensating for the power losses experienced at altitude [62]. Additionally, optimizing tire inflation pressure can enhance traction and rolling resistance. Lowering tire pressure increases the tire footprint, improving grip on loose or uneven surfaces and minimizing slippage.

However, inflation pressure needs careful management; excessively low pressure can cause tire overheating, premature wear, and reduced fuel efficiency, while overly high pressure minimizes contact area and increases soil compaction, negatively impacting both traction and crop health. Modern technologies like CTIS [63] allow dynamic adjustments of tire pressure, enabling farmers to customize tire performance based on varying field conditions and transport needs. This flexibility maximizes operational efficiency by lowering rolling resistance on hard surfaces and improving traction in the field. While optimizing tire size and air pressure alone cannot completely restore the power deficit at high altitude, these adjustments significantly enhance ground interaction efficiency, boosting overall tractor performance and reducing fuel consumption. Furthermore, these passive interventions are typically low-cost, easy to implement, and compatible with existing tractor configurations, making them especially advantageous for small-scale farmers operating in mountainous regions capabilities of agricultural machinery under altitude-induced constraints.

5. Conclusion

This study investigated the performance challenges of the Massey Ferguson (MF) 385 2WD tractor in the high-altitude environment of Mount Bamboutos, Cameroon, where low air density reduces engine power and tractive force by 20-40%. Through a systematic literature review, various solutions were evaluated for their ability to address these challenges while prioritizing cost-effectiveness, simplicity, and sustainability for smallholder farmers. High-cost solutions, such as turbocharging and engine replacement, were deemed impractical due to their expense and maintenance requirements. Instead, passive drivetrain modifications, including adjustments to transmission and differential gear ratios, as well as tire size and pressure optimization, provide affordable and durable improvements in traction and fuel efficiency. Active engine-focused strategies, such as optimizing fuel injection timing and quantity, offer moderate benefits when combined with passive approaches. To facilitate adoption, we recommend subsidized retrofit programs, training on maintenance and calibration techniques, and partnerships with local cooperatives to enhance technical support. Future research should focus on field-testing these solutions and assessing their long-term impacts on soil health and agricultural productivity. By implementing these low-cost interventions and supportive policies, agricultural mechanization in highland regions can be significantly enhanced, improving food security and rural livelihoods.

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