IAgrE Student Awards

NOMINATION SUMMARY

IAgrE CNH Industrial Award ***please delete as appropriate:**		
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Name of course studied: BEng Honours Degree in Agricultural Engineering		
Period studied	**From: 2021**	**To: 2025**
Qualification to be gained: 2:1		
Project Title: The investigation of the effect of separate hydraulic reservoir on oil contamination on tractors		
Details of material submitted with nomination: (Project/Exec Summary/videos etc) Honours Engineering Project		
SIGNED BY PROPOSER:	**DATE SUBMITTED:** **19-09-2025**	

If you wish to provide any additional information to support this nomination, please do so in a covering letter. When complete, return this form, together with the supporting documents, to

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THE INVESTIGATION OF THE EFFECT OF SEPARATE HYDRAULIC RESERVOIR ON OIL CONTAMINATION ON TRACTORS

by

BEDWYR DAVIES

being an Honours Engineering Project submitted in partial fulfilment
of the requirements for the BEng Honours Degree in
Agricultural Engineering.

2025

HONOURS ENGINEERING PROJECT ASSESSMENT FORM

<u>Student Declaration Form for Submission with Major Projects</u>

Section 1

This form must be completed by the student and included at the beginning of the Honours Engineering Project.

Candidate's Name	Bedwyr Davies
Candidate's Number	21250900
Degree Programme	BEng (Honours) Degree in Agricultural Engineering
Supervisor	Dr Sven Peets and Mr Graham Higginson
Major Project Title	The investigation of the effect of separate hydraulic reservoir on oil contamination on tractors
Word Count	10560
Confidential?	N/A

In submitting this Major Project I acknowledge that I understand the definition of, and penalties for, cheating, collusion and plagiarism set out in the assessment regulations. I also confirm that this work has not previously been submitted for assessment for an academic award, unless otherwise indicated

(Electronic) Signature of student: BTDavies

Date: 12th May 2025

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Glossary of Terms/Abbreviations

ANOVA – Analysis of Variants
CML4 – Contamination Monitoring Laser (model 4)
EHR – Electronic Hitch Regulation
HAU – Harper Adams University
hp – Horsepower
ICP – Inductively Coupled Plasma
ICP-MS – Inductively Coupled Plasma Mass Spectrometry
ICP-OES - Inductively Coupled Plasma Optical Emissions Spectroscopy
ISO – International Organisation for Standardization
JD – John Deere
mg/kg – milligrams per kilograms
PC – Personal Computer
PPE – Personal Protective Equipment
ppb – parts per billion
ppm – parts per million
rpm – Revolutions per minute
TRA – Transmission
HYD – Hydraulic

Element terms/abbreviation

Al – Aluminium
As – Arsenic
B – Boron
Ba – Barium
Ca – Calcium
Cd – Cadmium
C – Carbon
Cr – Chromium
Cu – Copper
Fe – Iron
K – Potassium
Mg – Magnesium
Mn – Manganese
Mo – Molybdenum
Na – Sodium
Ni – Nickel
P – Phosphorus
Pb – Lead
Se – Selenium
Si – Silicon
S – Sulphur
Sn – Tin
Ti – Titanium
Zn – Zinc

HCl – Hydrochloric Acid
HNO_3 – Nitric Acid
H_2O_2 – Hydrogen Peroxide

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ChatGPT has been used to generate initial ideas and improve vocabulary.

Summary

This study examines oil contamination levels in agricultural tractors with separate hydraulic reservoirs. A combined transmission and hydraulic reservoir on John Deere models were evaluated against a separate hydraulic reservoir system equipped on Fendt tractors. Oil samples were analysed using the ISO 4406 guidance for particle counting, particularly in the threshold of >4 to >14µm. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was paramount to assess chemical contamination including wear metals, such as iron and tin.

Fendt’s transmission oil demonstrated the cleanest results (ISO 23/21/20), while the Fendt hydraulic reservoir (HYD2) was similar to John Deere’s (ISO 24/23/18). Fendt HYD1 showed higher contamination rating of (24/23/21) reflective of maintenance practices followed.

ICP-MS analysis identified increased wear metals such as aluminium (Al), copper (Cu), iron (Fe), and tin (Sn) in the contaminated oil, from wearing components such as pumps, gears, and bearings. Fendt HYD1 had the highest levels of Al and Fe, while Cu showed a notable increase in Fendt’s transmission oil (TRA), which had no trace of Cu in the new oil samples. Sn was detected across all reservoirs, with John Deere’s combined hydraulic and transmission oil showing the highest increase. Changes in additive elements like calcium (Ca) and zinc (Zn) were also observed, with reductions in Zn in Fendt HYD1 and John Deere.

The findings demonstrate that the separate reservoir design, reduces cross contamination, enhancing component protection and could extend service intervals. This research supports the concept that a separate hydraulic systems will improve tractor performance and reduce maintenance cost in agricultural operations.

Chapter 1: Introduction

1.1 Background

The hydraulic circuit is a crucial component of a tractor's functionality, providing the necessary power for various agricultural attachments and functions. This system is designed to convert mechanical energy from the engine into fluid power by a hydraulic pump, pressurising the hydraulic fluid. The pressurised fluid is used to perform a wide range of tasks such as lifting, steering and operating attached implements. Key components of the hydraulic system include the pump, reservoir, control valve, filters, hoses and cylinders all of which work in tandem to ensure smooth efficient operation (Singh and Suhane, 2014). Through harnessing fluid power, tasks can be carried out with precision and minimal physical effort.

Increasing costs across the agricultural sector have led to a shift in consumer behaviour when purchasing equipment, as frequently upgrading to newer models is no longer financially viable. The longevity of components has become crucial, with a greater emphasis on maintenance due to the increased cost of regular service intervals and hydraulic oil change (Horne, 2023). Manufactures specify the required oil for their tractors, often insisting on using their own brand to avoid breaching warranty contracts. As the cost of equipment continues to rise, farm to farm implement sharing is becoming a more practical option (Hill, 2025). However, this practice does result in the equipment being used by various tractor brands with different hydraulic specifications, increasing the risk of oil contamination through mixing of individual manufactures oils from hydraulic pipes and cylinders.

This study will compare two hydraulic system designs: 1. A separate reservoir for both hydraulic auxiliary's and transmission oil, and 2. oil from transmission reservoir suppling both functions. First design is found on Fendt tractors, second design is found on a range of tractors. In this study John Deere was chosen as it is the most accessible brand for sampling. Samples from each brand system will be analysed to assess dirt contamination levels and evaluate the advantages of each system. Utilising instrumentation to analyse contamination in hydraulic oil offers several benefits, allowing accurate identification of the root cause of contaminants, such as particles, water and wear metals providing a clear understanding of the oils condition.

Understanding the probable cause of hydraulic oil contamination is crucial for maintaining system performance and longevity. Contaminants can degrade the oils effectiveness, leading to increased friction on wearing components and potentially resulting in system failure. Identifying the possible benefits of having a separate reservoir to reduced cross-contamination, between the oils used for transmission and auxiliary functions. Reducing frequency of oil changes enhancing system efficiency, lowering maintenance costs.

1.2 Aim

The aim of the project is to investigate the effect of external secondary hydraulic reservoirs on oil contamination in tractors, as an asset to reduce component wear.

1.3 Objectives

1. Review literature on tractor hydraulics, causes of oil contamination, quantification of contamination and the effect of contamination on component wear.
2. Develop methodology for acquiring primary data on hydraulic oil contamination on tractors and quantification of hydraulic oil contamination.
3. Implement methodology through collecting oil samples and maintenance details.
4. Analyse and evaluate the results in terms of contaminants, hydraulic system design and comparative level of contamination.
5. Draw conclusions on the effect of separate reservoir and the implication on component wear.

Chapter 2: Review Of Literature

2.1 Introduction

The hydraulic circuit is a crucial aspect of a tractor's functionality, as it provides power for various agricultural attachments and functions. To determine suitable methodology of functionality of a hydraulic system and possible improvements to develop desired measurement parameters, it is essential to review existing literature. This includes exploring various analysis techniques to quantify contamination levels.

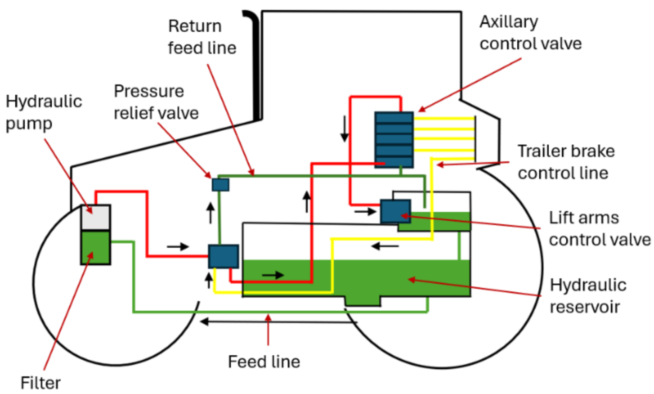
2.2 Tractor hydraulic function

The hydraulic function of a tractor works through conversion of mechanical energy from the engine into hydraulic power, it is an essential factor for the operation of onboard subsystem and provides power and functionality for attachment (Pabsetti *et al.*, 2023). Hydraulic systems have been in development since 1647, when Pascal's Law was discovered. Joseph Bramah applied this principal to create the first of its kind Bramah press, which was granted a patent in 1795 (Shekokar *et al.*, 2025). This innovation highlighted the effectiveness and compactness of the hydraulic design. Utilising Pascal's Law, hydraulic oil can transmit an evenly distributed force with small inputs that generate a larger output force (Ramesh *et al.*, 2019).

2.3 Hydraulic system design

2.3.1 Key components

The hydraulic system on a tractor is made up of several key components, as shown in (Figure 1). The core component of the hydraulic system is the hydraulic pump, which pressurises the hydraulic fluid generating the necessary flow for the system (Stoss *et al.*, 2013). Hydraulic fluid serves as the medium to transfer the required force while lubricating and cooling the system. To control the flow and direction a control valve is required. The control valve is used to regulate the speed and direction of systems such as the steering and 3-point linkage lift arms (Sun *et al.*, 2022). Through utilising the pressurised fluid within the hydraulic cylinders, a linear motion is created enabling tasks such as lifting and tilting. Hoses and hydraulic fittings are used to connect the systems component to ensure efficient fluid flow. The reservoir stores the hydraulic fluid and helps regulate its temperature. To prevent excessive pressure on the system, a pressure relief valve is fitted, which allows excessive pressure to divert back to the reservoir if required (Renius, 2019).



(Source: Adapted from Ferrari, Marani and Ghorpade, 2015)

Figure 1. Basic hydraulic circuit function on tractor.

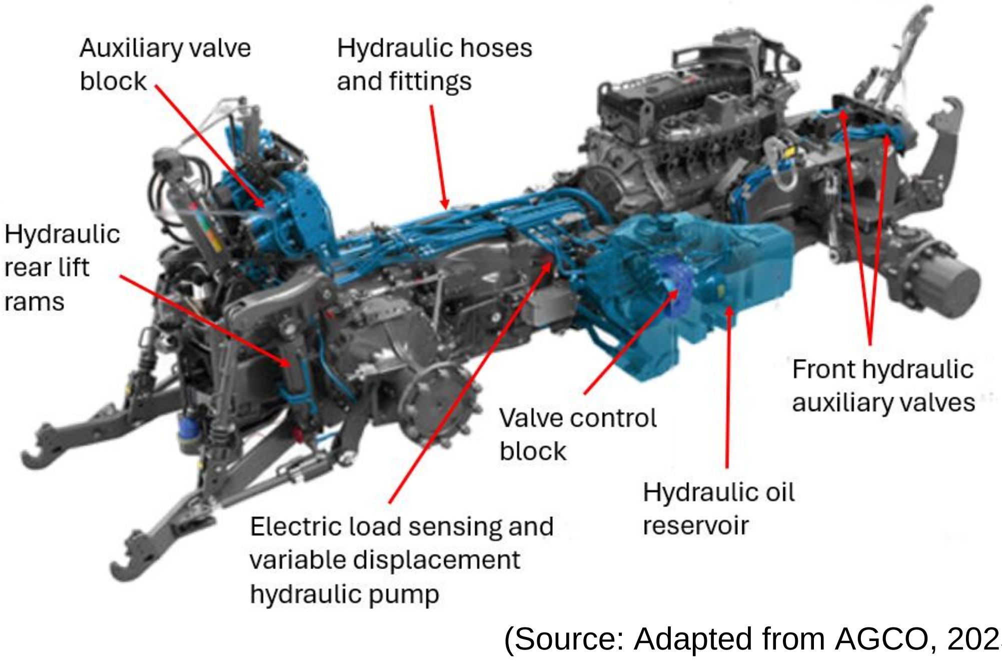
2.3.2 Manufacture hydraulic system comparison

AGCO manufacturing Fendt design

Fendt tractors run a separate reservoir for hydraulic and transmission, ensuring optimal performance is achieved without interference with one another. The hydraulic system has its own dedicated reservoir (Figure 2) to store hydraulic fluid, that powers onboard hydraulic systems and auxiliary implement operation. The separation ensures that the hydraulic fluid can be kept at the correct viscosity and temperature for smooth and reliable operation.

The Fendt Vario tractors transmission has a separate oil reservoir with specific oil requirement for optimal performance. This system reduces interference and cross contamination through mixing of the transmission and hydraulic oil, reducing the change in viscosity characteristics (AGCO, 2025). The separation enhances the integrity of both systems over time with oil suited to specific operational requirement. Each system has been designed with an individual cooling mechanism to prevent overheating and separate tanks to simplify maintenance, enabling independent oil changes with reduced downtime.

The hydraulic system operates in a continuous loop, which starts and ends within the dedicated hydraulic oil reservoir. Oil flows through a suction line to an electronic load sensing variable displacement hydraulic pump (AGCO, 2025) from the reservoir, adjusting flow and pressure based on demand improving system efficiency, with a pressure relief valve situated within the loop with a direct link to the low pressure return lines. Once the oil is pressurised, it travels through hydraulic pipes to an array of components including selectable control valves, steering system and lift arms (Renius, 2019). The functions are managed and adjusted electronically from internal operator cab controls, changing the timings and flow rate as required. The oil enters the set pressurised hydraulic cylinders and motor to perform mechanical tasks. Completion of the required hydraulic task allows the low pressured oil to return to the system circuit via return lines. Prior to returning to the tank, the oil passes through a filtration system to remove any contaminants whilst passing through the oil cooler before re-entering the reservoir.



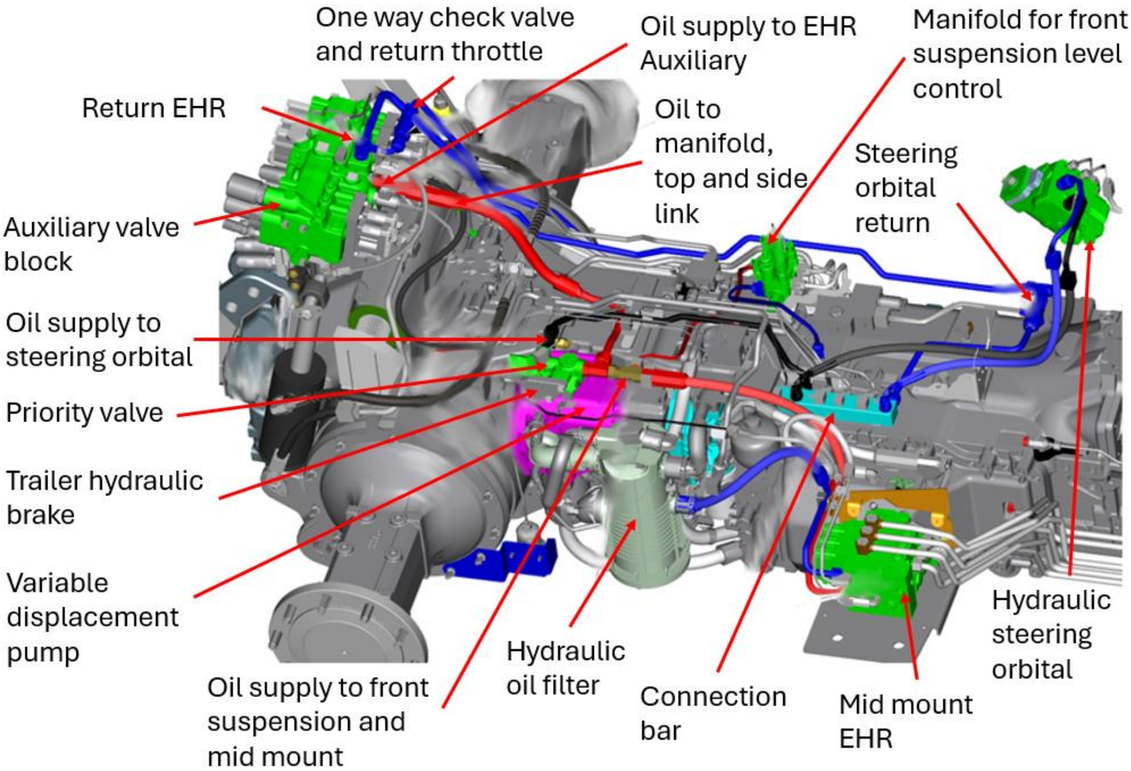
(Source: Adapted from AGCO, 2025)

Figure 2. Fendt hydraulic layout and reservoir location.

John Deere manufacturer hydraulic design

John Deere's share a reservoir for both transmission and hydraulic oil, using a single fluid to perform both hydraulic and transmission function. The integrated system was designed to simplify maintenance and enhance operator usability, with the need to only monitor and change one fluid, reducing cost through a single oil type purchase (Majdan *et al.*, 2016).

The hydraulic system cycle starts with oil being drawn from the reservoir into a variable displacement load sensing pump delivering pressure and flow to meet demand (John Deere, 2025). The oil powers both hydrostatic drive motors within the continuously variable transmission (given this transmission system is fitted to the tractor), ensuring smooth variable control and provides power to various hydraulic functions including the steering selective control valves, three-point linkage and auxiliary attachment (Renius, 2019). The functions are managed through the in-cab control interface allowing precise adjustment of flowrate and timing control. The hydraulic oil then returns to the reservoir through the return hydraulic hose lines after passing through the filter and oil cooler. The hydraulic fluid acts as a lubricant for internal gears and differentials including oil immersed brakes and clutch. The main hydraulic components with internal hydraulic reservoir design (Figure 3), with the red bypass representing pressurised flow lines and the blue indicating return hydraulic flow.



(Source: Adapted from Woolley, 2025)

Figure 3. Hydraulic system of combined reservoir layout.

2.4 Oil characteristics

2.4.1 John Deere oil

John Deere recommends the use of Hy-Gard oil, which has been formulated to meet high pressure and transmission demands whilst maintaining the necessary properties for efficient hydraulic performance. John Deere have run extensive comparison tests against their own brand and competitors in five crucial component areas of oil requirement. Hy-Gard transmission oil has proven a reduction of up to 20% less gear wear and 15% increased performance of the wet clutch function, reducing wear for a smother reduced slippage pattern and proven to reduce brake shatter by 24% (John Deere, 2020).

Performance testing of oil oxidisation consists of maintaining system temperature at 160°C for 400 hours with continuous air injection, using alternative competitive oil identified an increase in viscosity and sludge deposits in comparison to Hy-Gard oil, where near to no deposit were found increasing longevity of the product (John Deere, 2025). John Deere has developed an industry recognised slow-cool fluidity test to identify and validate the oils oil viscosity performance to ensure reduced down time and operational cost. Factors which are necessary to maintain adequate flow at low temperatures.

2.4.2 Fendt transmission oil

Fendt Extra Trans 10W-40 is developed to facilitate low temperature flow and provide instant response within the hydraulic system from cold start, ensuring consistent viscosity providing flow to operate and sufficiently lubricate moving components (AGCO, 2019). The oils development for proven consistency in viscosity stability allows increased component protection and high performance with low volatility to minimise internal oil consumption and wear.

2.4.3 Fendt hydraulic oil

Fendt Hyd 46 hydraulic oil has been developed to provide protection across a wide range of operating temperatures to meet the demand of extreme operating conditions within the agricultural and off-highway sector. Designed to provide advanced hydraulic efficiency, clean performance and thermal stability with reduced oxidisation (AGCO, 2014). Developed with high level of anti-wear properties and film strength for system protection.

2.4.4 Multipurpose oil

AGCO multipurpose tractor 15W-30 oil is a universal lubricant produced to reduce misapplication, with recommended use for hydraulic system, transmission and wet brakes (AGCO, 2015). Being one of the few oils tasked to provide functions to both systems as a lubricant and hydraulic fluid (Majdan *et al.*, 2016). The advantage of using universal oil leads to lower cost and reduced stock inventory for consumer, with proven cold start fluidity for instant response from the hydraulics with effective wet brake performance and additional additive protection (AGCO, 2015).

2.4.5 Characteristics comparison

Table 1. Comparison of oil characteristics.

Characteristics	John Deere Hy-Gard	Fendt Transmission	Fendt Hyd 46	AGCO Multipurpose
Viscosity	SAE 10W-30	SAE 10W-40	ISO 46	SAE 15W-30
Density at 15°	873kg/m3	0.866	N/A	0.886
Flash point	220°	162°	198°	200°
Pour point	-40°	-37	-54	-37
Viscosity Index	141	154	168	120
Viscosity at 40°	59.2	80.74	46.24	79.0
Viscosity at 100°	9.4	12.54	8.64	11.0
API	GL-4	GL-4	N/A	GL-4

Source: Adapted from John Deere (2020); AGCO (2019); AGCO (2014); AGCO (2015).

2.5 Additives in oil

Hydraulic and transmission oil primarily consist of base oils and additives, with base oil making up 70-90% of the fluid. Base oil can be made up of minerals that are derived from crude oil, synthetic that's chemically engineered or plant based biodegradable oils. To make up the remainder additives are added, making up between 10-30% to enhance the oils properties and stability (Schneider, 2006). The selection of base oil and additive requirement is dependent on manufacturer component specification and performance requirement, taking into consideration environmental considerations, oxidisation resistance and temperature stability in the working environment (Obasi and Udeagbara, 2014).

Concentration of chemical elements in tractor hydraulic oil is crucial, to ensure that the oil performs effectively under a range of operating conditions. The elements are commonly found to be additives added to enhance oils properties improving lubrication, reduce component wear with foam formation control and prevent rust or corrosion of key working components. Four common elements found in hydraulic oils include zinc (Zn), phosphorus (P), calcium (Ca) and boron (B) (Kosiba, Vozarova and Petrović, 2018). Zinc is an element used as part of the anti-wear additive to protect components through forming a protective film on the metal surface with zinc dialkyldithiophosphate (ZDDP) being a recognised compound element of zinc. Phosphorus plays a similar role as an additive to zinc (Puhan, 2020). Calcium (Ca) and magnesium (Mg) commonly found in detergents and dispersants, neutralise acids within the hydraulic oil to prevent sludge formation and oxidation of component, hence enhancing oil cleanliness within the system (Máchal *et al.*, 2013)

Boron (B) is added as a friction and anti-wear compound modifier to improve the oil's ability to maintain a stable viscosity in high pressure changing conditions. Sulphur (S) and molybdenum (Mo) are commonly used for high pressure additives, reducing metal to metal contact and internal component friction leading to excessive wear. Barium (Ba) is added to reduce and prevent foam formation of the hydraulic oil. Traces of copper (Cu) can be found in some additives to serve as a corrosion inhibitor to protect components (Pabsetti *et al.*, 2023). The additive elements associated within oil's all play an essential role in maintaining the efficiency and longevity of the hydraulic system on agricultural tractors, with the concentration of each element tailored to the specific need of manufactured components and attachments (O'Brien 1983).

Excessive use of additives in oil can lead to a negative effect on both hydraulic and transmission fluid. Excessive amount of anti-wear additives in hydraulic oil such as zinc (Zn) and phosphorus (P) can result in sludge formation, blockages of filters or valves and degrade seal quality. Another cause of sludge build up is an increase in antioxidants that can interfere with the oils cleaning properties properties (Ahmed and Nassar, 2011). Overuse of foam inhibitors can have a negative effect resulting in pump cavitation, with viscosity oil modifiers potentially reducing oil flow through increased thickness.

Both hydraulic and transmission oil require careful balance of additives to achieve optimal system performance and provide sufficient temperature resistance, lubrication and anti-wear properties (Baderna *et al.*, 2011). Their specific needs can differ due to unique system demand, as hydraulics are required to perform effectively across a broad range of pressure and temperatures. In comparison transmission fluid requiring a more controlled viscosity range, to enable synchronised smooth gear change, with an increase in friction modified additive. Whereas a hydraulic system requires reduced friction modifiers to avoid pump and valve slippage (Pabsetti *et al.*, 2023).

2.6 Oil contamination

2.6.1 Type of contamination

Oil contamination within agricultural tractor hydraulic system refers to the presence of foreign materials within a fluid that can reduce performance, increase system wear rate and cause hydraulic system failure. There are four main types of contaminants that range from solid particles, water, air and chemical additive degradation that enter the system (Zeng *et al.*, 2016). Solid contaminants can be made up from a range of contributors such as dirt, dust, rubber, plastic and metal shavings, that can occur from poor maintenance, worn components and dirty working environments. Metal particles occur from wear on internal components such as pumps, valves and cylinders, whilst rubber particles can occur from degrading hoses and seals of the hydraulic system (Zeng *et al.*, 2016).

Water ingress within the hydraulic system can occur through leaking seals, condensation or prior contaminated fluid, enhancing component corrosion rate and reduced system lubrication (Majdan *et al.*, 2019). Air introduced through leaks in suction lines and low oil level can cause breakdown of fluid, reducing performance capabilities and increased temperature of operating components. Chemical contamination can occur when oil is not mixed to the recommended specification through cross contamination of oils and oxidisation overheating the system, breaking down the fluids additive function (MAČUŽIĆ and JEREMIĆ, 2004).

2.6.2 Effect of contamination

Hydraulic system component wear occurs from increase in internal contaminants from working components. This can occur through metal filing particles generated from the pump, leading to scoring and damage of internal surfaces reducing operational function (Majdan *et al.*, 2019). (See section 2.7 for ISO category of particle size). The sediment dirt and water mixture can cause blockages and corrosion of hydraulic filters, with worn seals allowing an increase of contaminants and cause of oil leakage. Rubber debris from perished hoses can damages seals and block valves, with air contamination leading to cavitation and reduced product lifespan (Șcheaua, 2024).

Due to the working environment of agricultural vehicles, they are more vulnerable to increased contamination levels as they operate in harsh, dusty and wet environments, making their hydraulic system more prone to internal contamination causing extended damage if not monitored. The performance of the system is crucial for everyday working tasks, such as operation of steering, implements and braking system of the tractor, with contaminated failures leading to significant operational downtime (Majdan *et al.*, 2016). Most hydraulic manufactured components have specified acceptance tolerances of oil contamination filtration that aliens with ISO 4406, such as a flow diverter with specified 21/19/16 up to 150 bar and over 150 bar 20/18/15 ISO code to guarantee a longer duration of pump through eliminating any oil impurities (Galtech, 2018). ISO 4406 code relation to hydraulic operating components (Table 2).

Table 2. Recommended tolerance contamination level for pressure below 140 bar.

	ISO 4406 code				
Component	20/18/15	19/17/14	18/16/13	17/15/12	16/14/11
Piston pump fixed flow rate.	•				
Piston pump with variable flow rate.			•		
Vane pumps with fixed flow rate.		•			
Vane pump with variable flow rate.			•		
Hydraulic cylinders	•				
Actuators					•
Check valves	•				
Directional valves	•				
Flow regulating valves	•				
Servo valves					•
Plain bearings			•		
Ball bearings				•	

(Source: Adapted from MP Filtri, 2022)

2.6.3 Contamination prevention

Enhanced maintenance practices are key steps to prevent contamination with appropriate use of filtration systems, scheduled filter changes and ensuring oil reservoirs remain sealed, free from dirt and moisture. Important to follow the manufacturer's recommended oil's, to avoid cross contamination of brand mixing and formulation (DES-CASE, 2019). The storage of new clean oil is essential, to be kept in dry sealed containers to avoid any prior oil contamination entering the vehicle system. John Deere combined reservoir has an on-board oil storage capacity of 81 litters of Hy-Gard oil for transmission and hydraulic function. Changing both hydraulic and transmission oil filter every 700 operating hours, after the first 100 operating hours of the tractor (John Deere, 2022).

Fendt has an on-board storage capacity of 80 litters of hydraulic oil, with extended service interval of 2000 operating hours or 2 years. It is possible to run bio hydraulic oil through the additional hydraulic reservoir, although a more regular service interval of 1 year or 1000 hours is required (AGCO, 2025). Fendt manufacture recommends that transmission oil is changed every 2000 operating hours, changing the pressure filter and suction filter every 1000 hours after the first 50 hour service with capacity of 50 litters (Maple Lane Farm Service, no date).

2.7 Contamination analysis technique

There are two fundamental hydraulic oil analysis techniques used to monitor oil condition and predict system wear, such as a particle count analyses and spectrometric oil analysis.

Particle count analysis is used to measure quantity and size of solid particles within the oil. This technique is performed in line with the ISO 4406 standard using instrumentation such as the MP Filtri particle counter (MP Filtri, 2022). The system works using an automatic laser particle counter and can be used remotely on site or in a laboratory setting (MP Filtri, 2022). It categorises particles into three critical size ranges: >4µm, >6µm and >14µm. Range >4µm includes particles of >6µm and >14µm, and range >6µm includes >14µm. From this an ISO cleanliness code is generated such as 21/20/18 that indicates whether the oil meets predefined cleanliness criteria for safe and efficient system operation (Table 3) (ISO 4406, 2021). The ISO cleanliness rating is adopted by manufactures of components such as Rexroth Bosch group, for components such as solenoid operated valves direct acting spool with a recommended fluid degree of contamination no more than 19/17/14 max 10µm (Rexroth, 2017).

Table 3. Recommended oil contamination level in relation to ISO 4406 for component wear.

Contamination ISO code	Application
18/16/13	Very sensitive, high reliability systems with proportional valves and pressure > 160 bar.
19/14/11	Vane pumps and piston pumps.
20/16/13	Modern industry hydraulic systems, directional valves and pressure valves.
20/18/14	Sensitive reliable systems.
21/17/14	Industrial hydraulic systems with large tolerances and low dirt sensitivity.
21/19/16	General equipment of limited reliability.
23/21/18	Low pressure equipment is not in continuous service.

(Source: Adapted from Rexroth (2013); MP Filtri, (2021) Inductively Coupled Plasma Mass Spectrometry (ICP-MS) offers high sensitivity detection of trace metals to parts per billion (ppb) level, making the equipment an effective tool for long term trend monitoring and early detection of component wear (Lienemann *et al.*, 2007). This method provides a detailed chemical profile of the hydraulic oil by identifying element composition and concentration of wear metals such as iron and copper, containment of silicone and sodium providing a detailed composition of additional additives like zinc dialkyldithiophosphate (ZDDP) (Majdan *et al.*, 2016). However, ICP-MS can be a time-consuming method requiring meticulous sample preparation, to reduce sample interference and avoid contamination affecting analytic accuracy of the hydraulic oil sample data results (Lienemann *et al.*, 2007).

While both techniques differ in individual focus from physical particle characterisation and chemical composition, the range of previous literature research consistently compliments their combined use to verify one another (Vähäoja 2006). A study on excavators' hydraulic system (Ng, Harding and Glass, 2017) demonstrated through the integration of real time particle counting, image analysis and ICP creating an in-depth understanding of machine oil condition. Additionally, a review by (Marko, Mitar and Velibor, 2020) of the analysis tool for combined application demonstrates the theoretical framework supporting the need for advanced justification of contamination and prevention maintenance, with this approach enhancing both diagnostic accuracy and maintenance intervals.

Standardised sampling protocol are essential to support the effectiveness of quantification technique. Samples should be taken from consistent representative points, such as the pump drain and return lines to gauge full dirt contamination cycle, ensuring that clean sample containers are used to prevent external contamination (Hujo *et al.*, 2021). The interpretation of data should follow established benchmarks such as ISO 4406 cleanliness code, aligning with severity of service conditions and manufacturer system maintenance practices (ISO 4406, 2021). Through the combined use of an ICP-MS and image particle analysis within structured sampling and monitoring technique. This provides a robust foundation for data driven results and a guide for maintenance strategy enhancing early fault detection, reduced downtime and extended equipment components durability.

2.8 Knowledge gap in contamination analysis

Previous research projects focusing on the detection and monitoring of hydraulic oil contamination in industrial and commercial machinery systems have been investigated. The studies have commonly explored various technique such as particle count analysis and spectrometric methods to evaluate oil condition and identify the presence of wear metals and external contaminants. Previous literature aligns with laboratory-based analytics and monitoring tools in terms of accuracy sensitivity and practicality of the method. However, there has been limited investigation into how the effect of external auxiliary functions influence the rate of hydraulic oil contamination or the effect of integrated hydraulic oil reservoir with the transmission. A range of studies have explored the long-term degradation pattern of hydraulic oil (Hujo *et al.*, 2021) under a range of variable loading conditions and equipment attachment. However, there is limited data available for direct comparison of the findings from this investigation.

Understanding the contamination behaviour of hydraulic oil in industry working vehicles application is critical for manufactures and development teams seeking to implement advanced protection technologies and make informed design improvements. Such insights contribute to enhancing component durability, reduced wear and increasing the overall competitiveness of equipment design. Minimising contamination related failures to supports more accurate prediction of component longevity, offering valuable data to strengthen warranty strategies and improve customer confidence in product reliability.

Chapter 3: Methodology

3.1 Introduction

A clear and reliable methodology must be established for sampling and testing hydraulic oil, assessing contamination levels accurately in accordance with ISO 4406 standard. To achieve acceptable data, specialist instrumentation capable of capturing and analysing both particulate and element contamination within the oils is required. For the purpose of analysis, the study will utilise an MP Filtri in line particle counter to classify solid particle contamination CML4, along with an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for detailed chemical analysis of wear metal and additive elements. Utilising the analysis tools to evaluate hydraulic oil contamination samples, to identify the cleanliness benefit of reduced dirt contamination through having a separate hydraulic tank, providing a comprehensive understanding of contamination behaviour. Selection of appropriate machinery, sampling location and analysis equipment has been outlined in this section to ensure consistency and reliable data collection.

3.2 Tractor specification selection

For this study it was essential to select two tractor brands for comparative analysis. Ten Fendt tractors were chosen due to their distinct hydraulic system design, featuring a separate hydraulic oil reservoir where 20 samples would be collected. Ten John Deere tractors were chosen as a second brand, which have a shared hydraulic and transmission reservoir, a more common manufacturing design meaning only ten samples were collected because of a single reservoir. This provides 10 samples per tractor with an additional 10 for Fendt providing 30 contaminated oil samples in total which is suitable for statistical testing (Hertzog, 2008). It was possible to access John Deere tractors as a comparable model range at a single farm location.

Key specification parameters were established for both brands, these included the use of variable drive (automatic) transmission, as well as the chosen tractors falling within similar horsepower (hp), all having undergone comparable operational work tasks. This approach was intended to minimise performance variation due to design differences unrelated to hydraulic systems. The selected John Deere models used in the study were from the 6R series, with specific models ranging from 6R 165 to 6R 250, and Fendt models ranged from 700 series up to 1000 series, a wider range due to difficulty accessing a similar size range.

3.3 Location selection

Collection of data from several different agricultural tractors, required a farm or agricultural contractor yard, to provide suitable sample collections and achieve the number of required samples from similar tractor brands and drive train transmissions. The first site of choice to acquire data samples was HAU farm, with ease of access to the vehicles. However, this option was infeasible, due to the limited number of agricultural tractors available and range of transmission options, reducing product range similarity.

To acquire the 10 John Deere and Fendt agricultural tractors within the criteria range of similar horsepower, transmission and maintenance interval, it was required to sample the oil at two external test sites - Company A based in Caernarfon, North Wales (Fendt HYD1) and Company B based in Oswestry, Shropshire (JD HYD & TRA). These locations were chosen as they were able to provide a range of agricultural tractors and compatible equipment. However, a change in the weather resulted in limited access to the equipment at one of the farms. To acquire the additional samples for testing, it was necessary to arrange a visit to Company C, Newport, Shropshire (Fendt HYD2).

Company A contractor tractors had a wider manufacturing year registration age and followed their own service maintenance regime. The contracting company stuck to the 2000 operating hour service for transmission filters and 10w-40 transmission oil. However, for the sperate hydraulic reservoir adopted a 500 operating hour filter change and just toped up the oil with 15w-30 multipurpose oil, following any leaks or hose breakage when attached to the implement. Company B followed the manufactures recommended service intervals of filter and oil change every 700 operating hours as closely as possible, using John Deere’s own brand 10w-30 Hy-Gard oil. Company C is an arable farm and followed the manufactures recommended service interval of every 2000 operating hours oil change and 1000 operating hours filter change.

3.4 Analysis instrumentation

3.4.1 MP Filtri CML4

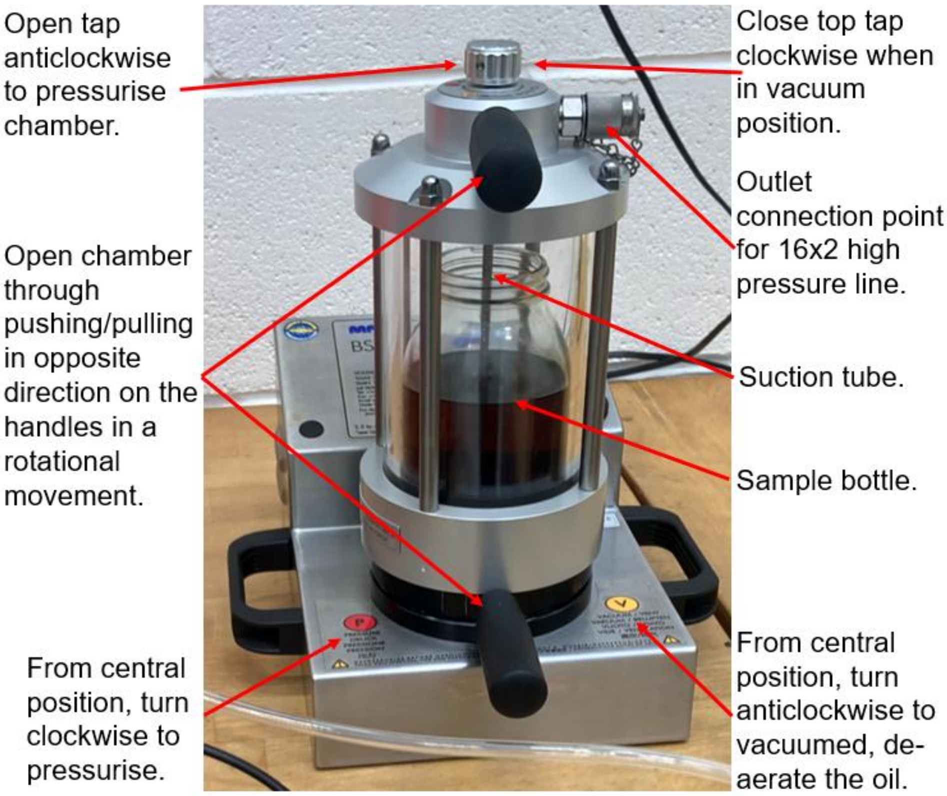
MP Filtri is a contamination monitoring system designed to measure solid particles in hydraulic fluids, adhering to ISO 4406 standards. The portable sampling unit operates through utilising a high precision LED light extinction automatic optical particle counter to detect and classify particles (MP Filtri, 2022). The devise can analyse oil from both pressurised and unpressurised systems, with the possibility of sampling oil from system test points, reservoirs and test samples with a built-in metering pump.

The MP Filtri sample device CML4W0M001 was selected to accurately measure oil contamination, offering a precise level of ±1/2 for ISO code for particle sample 4, 6, 14 µm and ±1 ISO code for large particle quantification 21, 25, 38, 50, 70µm (MP Filtri, 2022). The measurement device features a high-resolution touch screen interface used for setting up and configuration prior to sampling, as well as a real time visual display of contamination levels, (Figure 4) with optional Bluetooth physical data printer available for immediate documentation of results.

(Source: Author’s Own, 2025)

Figure 4. MP Filtri digital interface and Function.

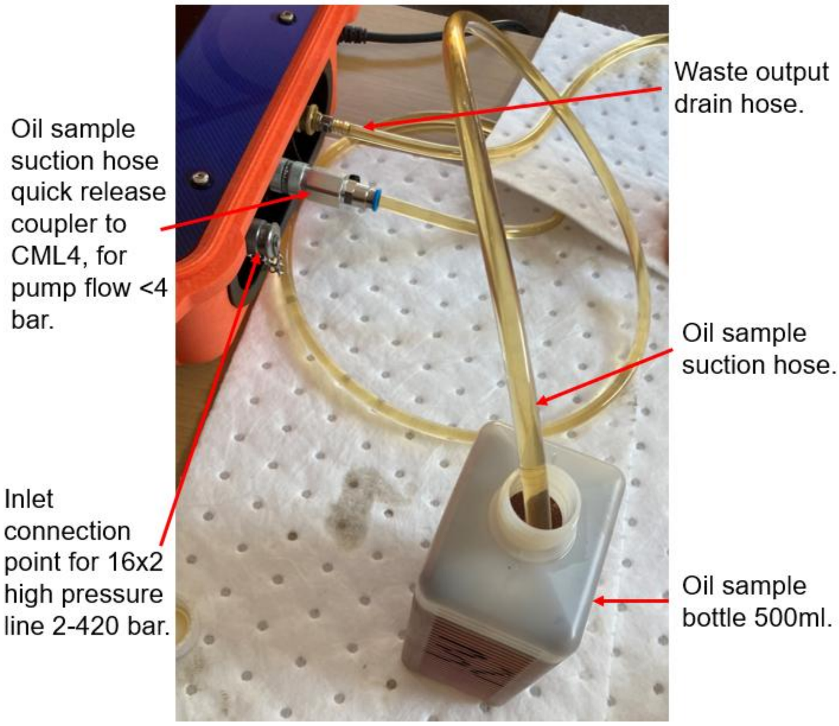
A fluid de-aeration unit BS500 bottle sampler proved suitable to transfer the hydraulic and transmission oil from the 500ml sample bottles, which is the largest size, that fits within the devise to transfer the pressurised oil to the CML4 analyser. The BS500 had two functions, once the sample was secured within the confined space, with a suction hose situated inside the bottle (Figure 5). First it was necessary to de-aerate the chamber and oil for reduced air bubbles, before turning to pressurised with an indicator changing from green to red once at acceptable pressure. Once pressurised the sampling process could commence.



(Source: Author’s Own, 2025)

Figure 5. RS500 pressure cylinder sampler function.

Due to contamination levels within the oil and its viscosity at the sampling temperature, the flow through the system was restricted, leading to inaccurate results. The reduced oil flow and increased presence of air bubbles compromised the reliability of the sample results. To improve the accuracy, a revised sampling method was implemented (Figure 6), utilising the built-in pressure pump. The pump featured a larger diameter suction hose and provided a more consistent flow through the sampling devise. As a result, the updated method delivered improved accuracy and reliable consistent results.



(Source: Author's Own, 2025)

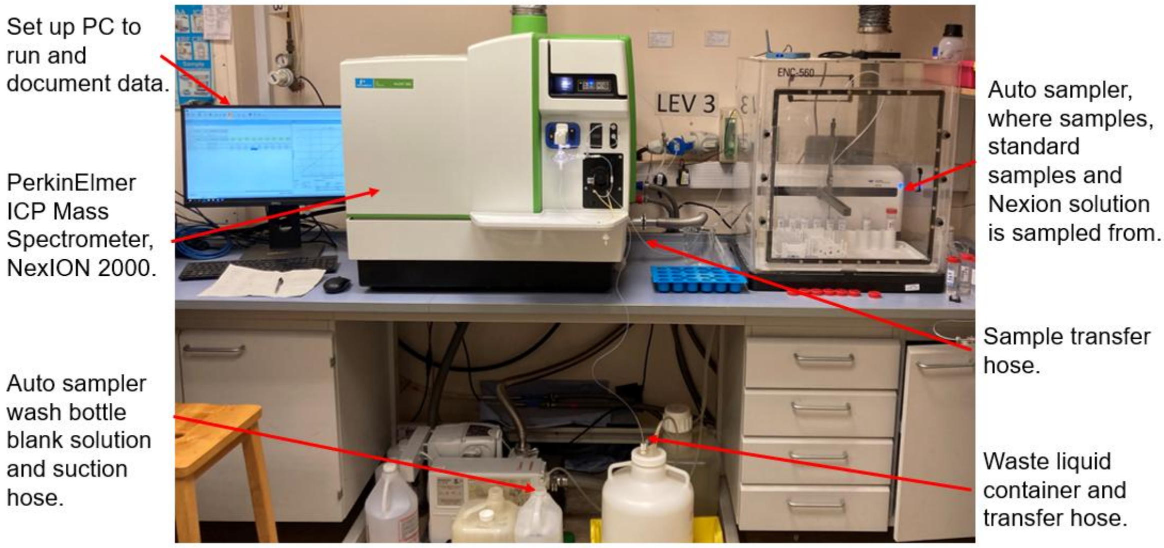
Figure 6. Revised sampling method using CML4 built in pump.

Following the analysis procedure using the MP Filtri CML4, it was noted that there was a reduced flow for the last two samples like the first sampling procedure, where debris was evidently flowing into the CML4 during the sampling procedure. The CML4 sampler was sent back to the manufacturer, finding that the inlet gauze was filled with contaminants being the cause of reduced flow (see Appendix 6).

3.4.2 Spectrometric analyser.

A review of literature on oil sampling and element analysis identified two commonly used analytic methods ICP-OES and ICP-MS. Given the resources and equipment available, it was determined that HAU laboratories only had access to a PerkinElmer Nexion 2000, serial 815N7120601B ICP-MS instrumentation (Figure 7) with preventative maintenance completed on 10/2024, which became the selected method for analysis. The ICP-MS is an adequate measurement technique to identify the level of contamination and comparison from base line oil, to identify wear contaminants and additive change.

As no prior oil analysis programs had been conducted at the HAU laboratories, it was initially uncertain whether the required analysis could be successfully performed. With guidance and literature findings, it was decided to adapt a previously established feed sampling method. Previous literature findings of elements used to identify contamination in oil gave a baseline of what chemical element to focus on such as Al, As, Ba, B, Ca, Cr, Co, Cu, Fe, Li, Pb, Mo, Mg, Ma, Ni, Se, Si, Ti, Zn, Ca, P, K, Na and S (Hujo *et al.*, 2021) allowing for calibration standards to be created. (See 3.5.3 Preparation for ICP-MS point 10).



(Source: Author's Own, 2025)

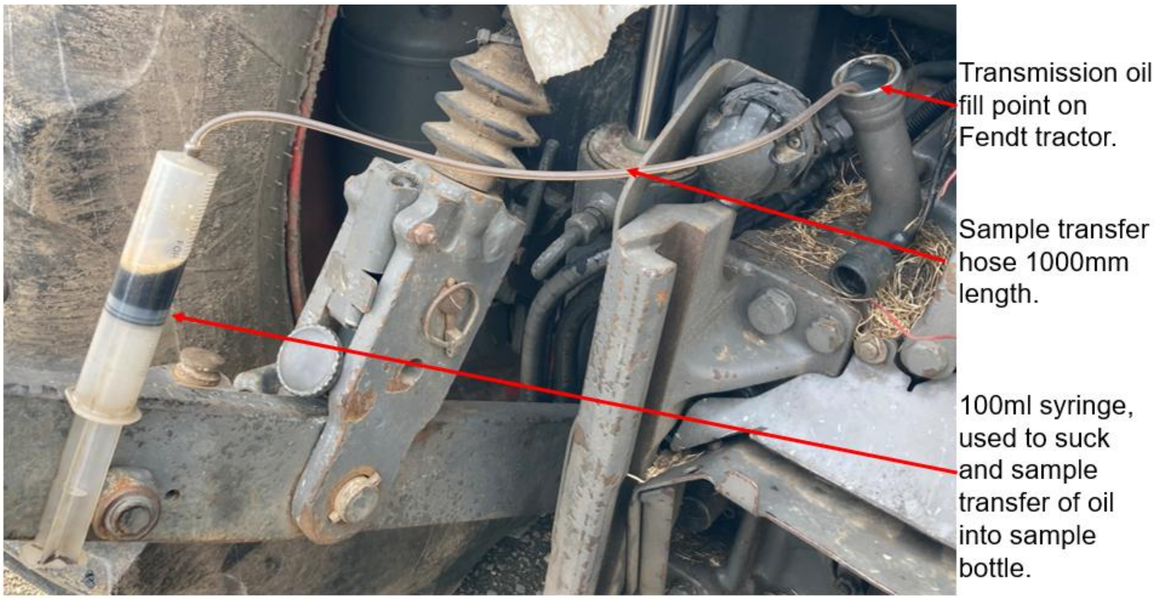
Figure 7. PerkinElmer NexION 2000 ICP-MS and auto sampler setup.

3.5 Experimental procedure

3.5.1 Sampling equipment

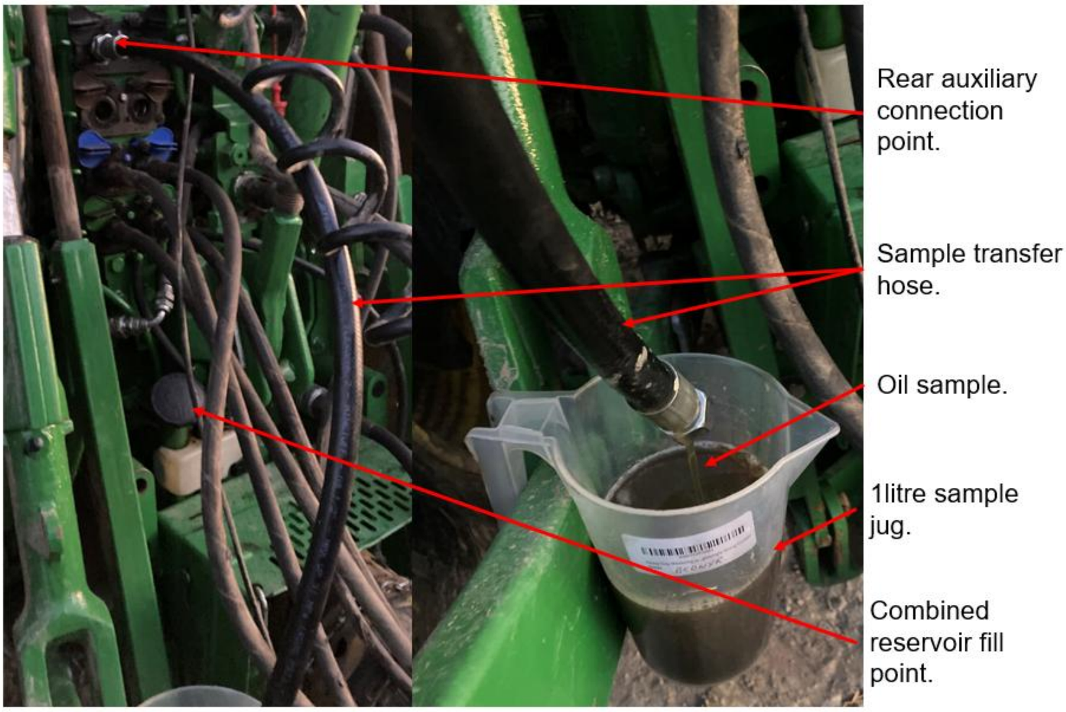
Before data collection could begin it was essential to gather all the necessary sampling equipment to ensure a smooth and efficient on-site sampling process to work around equipment availability and time constraints. A 500ml sample bottle was chosen as they were the largest size compatible with the RS500 sampler and provided a sufficient volume of oil for flushing residual oil prior to collecting and analysing samples. HAU laboratories provided 50ml sample collection test tube for oil collection to be used in the ICP-MS instrumentation.

To extract oil from the Fendt tractors a 100ml syringe and a 1000mm hose was used to draw the transmission oil out through the fill point (Figure 8). Hydraulic oil for both tractor brands was sampled via the rear auxiliary coupling, using a male ½ inch coupler and 1000mm hose. The oil was drained into a 1 litre jug by operating the hydraulic spool at a reduced flow rate (Figure 9) of approximately 1L/min through the in-cab screen interface control and transferred into the sample bottle. (See 3.5.3 for further details on collection process).



(Source: Author's Own, 2025)

Figure 8. Transmission oil sample procedure Fendt Tractors.



(Source: Author's Own, 2025)

Figure 9. John Deere and Fendt hydraulic sample collection point.

3.5.2 Experiment preparation

To minimise the risk of equipment malfunction, prior to oil sample collection each tractor underwent a thorough inspection, to ensure it was in good working order and that the oil fluid levels were at the correct fill mark. All vehicles were positioned on level ground before sampling commenced. A pre-start check protocol was followed to reduce the likelihood of mechanical issues or operator injury during the process.

Personal protective equipment (PPE) was required which included gloves, overalls, safety goggles and safety boots (HSE, 2022). Additionally, spill kits and cleaning rags were at hand to manage any spills (Health Safety Executive, 2015) as well as ensuring appropriate disposal of waste.

The MP Filtri CML4 had been calibrated on 14/10/2024 (Appendix 1) and hadn't been used since calibration, ensuring that it was fully operational and compliant with ISO 9001 standards. The ICP-MS was calibrated at the start of the sampling process with a pass or fail indicator demonstrated through running the provided manufacture element standard solution to verify instrument accuracy.

3.5.3 Data collection procedure

Prior to sample collection, it was necessary to heat and thoroughly mix the hydraulic oil within the system to the manufactures recommended calibration temperature, ensuring consistent and reliable sampling across all agricultural tractors in the study. To achieve the specified manufacture calibration temperature of greater than 25°C for John Deere (John Deere, 2013) and 40°C for Fendt tractors (AGCO, 2017), it was necessary to connect a hydraulic loop to the rear auxiliary coupling of each tractor and run the oil from the reservoir around the circuit for approximately 10 – 12 minutes, because Fendt hydraulic tank did not have temperature gauge and the average time took to heat up the combined reservoir was used (Figure 10).

(Source: Author's Own, 2025)

Figure 10. Hydraulic warm up loop attached to rear auxiliary to circulate the oil.

A pressure reducer was fitted to the hydraulic hose to limit the oil flow, allowing the oil to reach target temperature more efficiently. To maintain consistency and control temperature measure across all test vehicles, the pressure was standardised by fully closing the control tap and then rotating it three full turns clockwise past zero, returning the marker point precisely back to the zero mark. The pressure reducer used was an MHA NDV-DN12-G1/2 PN350 1A with single direction flow.

Sample collection method.

Collection of the oil samples for the John Deere combined reservoir and Fendt hydraulic reservoir were conducted using the following procedure, with access to all required PPE and equipment:

1) Accurate labelling and notation of each sample vehicle for traceability of oil sample.
2) Ensure initial tractor safety checks completed.
3) Hydraulic loop connected to the tractor and set pressure reducer.
4) Tractor started and moved to level ground if on a slope.
5) Tractor running at 1000rpm, placing the spool valve in flow position to heat up the oil to calibration temperature.
6) Once required temperature reached, place spool valve in the float position, allowing oil to drain from hydraulic hose and remove hose.
7) Connected sample hose to the tractor, reduce the flowrate and flush 100ml of oil through the hose into a jug pouring into a waste container, to reduce cross contamination of oil within hose.
8) Thoroughly clean the sample jug through utilising the spill rags to soak up excess oil before drying with blue role tissue ensuring no dirt or contaminants left behind.
9) Once jug has been cleaned collect approximately 600ml of oil through operating spool valve to fill 500ml sample bottle and 50ml laboratory test sample tube. Pouring any excess oil back into the tank.
10) Place the spool valve into float position and remove hose, on completion turn the tractor off.

    The above demonstrates the key process followed for John Deere samples with Fendt requiring additional steps for transmission sample collection.

11) Positioned at the rear of the tractor, clean around the transmission fill cap and open.
12) Place 1000mm hose down the fill cap and connect to 100ml syringe.
13) Pump syringe until oil suction flows into syringe.
14) Once half full, pour into the waste container as it flushes and removes any previous residual that might have been left in the hose.
15) Repeat steps 12 and 13, once the syringe is full poor into 500ml sample bottles and 50ml sample tubes.
16) Remove syringe and hose, return the excess oil back into the tank out of the hose and syringe, close the fill cap.

During sample collection at each individual site, a base line sample of 500ml and 50ml of clean new hydraulic and transmission oil was taken.

MP Flirty Data Collection

It is important to assess and wear the appropriate PPE in line with legislation guidance during sample analysis.

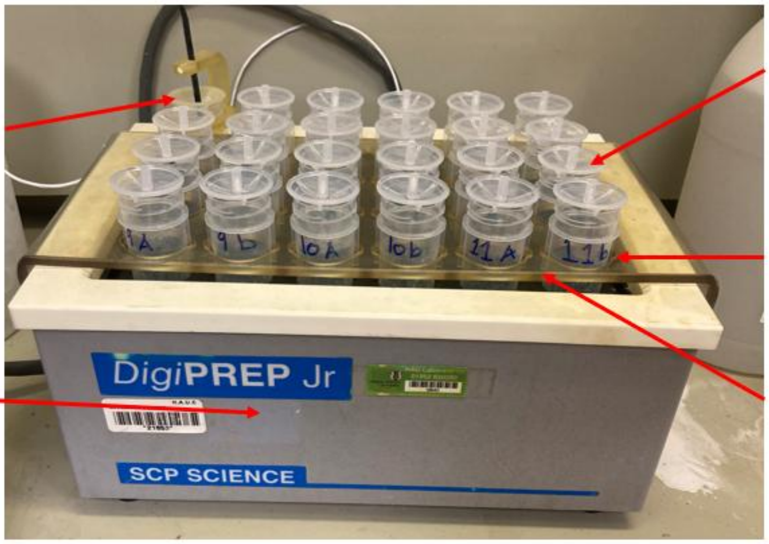
1) Place the MP Filtri CML4 on the work bench and connect to the mains power supply to ensure constant battery power operation throughout sample collection.
2) Connect suction hose and waste hose.
3) Place waste hose into waste collection container.
4) Turn MP Filtri CML4 unit on and select ISO 4406 standard.
5) Select suction pump at <4 Bar as the inlet option.
6) Select sample one, turn fully clockwise five times and then repeat anticlockwise to mix the oil and reduce standing settlement. Repeat process for all samples.
7) Place suction hose into 500ml sample bottle.
8) Select start on the digital-coloured interface of the unit, where the machine will flush 60ml through first from the sample and then a 60ml analysis sample.
9) On completion an ISO quantification standard of particle contaminants within the oil will appear on the screen interface.
10) It is possible to print, download and note the results on completion of each sample analysis. Repeat process for all samples.

ICP-MS data collection process.

All HAU laboratories health and safety guidance and procedures, wearing correct PPE and lab coat should be followed. (See Appendix 2 for full process breakdown)

<u>Oil preparation and digestion</u>

1) Weigh 0.5g of oil using a Kern and Sohn GmbH ABS 120-4, serial WB1100108 four place balance weigh calibrated on 20/05/24 from the collected 50ml sample, placing in clean DigiTube.
2) Necessary to duplicate each sample and recording as samples A1 and B1 for the analysis process as backup for one of the samples failing.
3) Once all sampled are weighed add 1ml of conc. HCl, 6ml of conc. HNO_3 and 5ml of conc. H_2O_2 to all samples to start the digestion process.
4) Place the sample rack of tubes into the slots of the DigiPREP Jr heating block, placing a plastic watch glass on top of each sample tube.



(Source: Author's Own, 2025)

Figure 11. DigiPREP Jr heating block.

5) Turn on the DigiPREP Jr and select Feeds method from the list as it's the chosen adapted method and begin the run process.
6) Once ran, dilute the cooled samples through adding ultra-pure water up to the 50ml mark on the DigiTUBE, closing the screw top lids and shaking before storing until prep for ICP-MS analysis.

<u>Preparation for ICP-MS</u>
ppm = mg/L
ppb = µl/kg

7) Creation of blank solution that contains 2% Nitric in a 1L volumetric flask is required for sample dilution.
8) An internal standard of 1000ppb is required to create a sample dilution acid for calibration, created through adding 1ml of conc. Nitric acid followed by 50µl of 100ppm Gallium stock solution and fill to the marker with ultra-pure water.
9) Creation of blank from step 7 allows for the creation of sample diluting acid through adding 10.204ml of 1000ppb Ga internal standard through using a 2-place analytic balance to weigh.

Reviewing previous oil sample analysis literature and additives in oil gave a base line of what elements to look for and identify in comparison to base line new clean oil.

10) Calibration standards are necessary for ICP-MS to identify any relation within the oil, to create first half fill 1liter volumetric flask with ultra-pure water, adding 20ml of conc. Nitric acid followed by 200µl of Al, As, Ba, B, Ca, Cr, Co, Cu, Fe, Li, Pb, Mo, Mg, Ma, Ni, Se, Si, Ti, Zn, 1000µl of Ca, P, K, Na and S 5000µl finalising the standard through filling ultra-pure water to the flask fill mark. Mix through inverting the flask 12-15 times.
11) Once calibration standards are created it is necessary to create working standards to place in ICP-MS (see Appendix 2 point 16).
12) Following the DigiPREP Jr digestion process steps 4 – 6, the samples are diluted 1:50 through pipetting 100µl of sample adding 4.90ml of sample diluting acid, that contains the internal standards into auto sampler tube.

13) Once all samples are mixed, place in auto sampler Teledyne ASX-560 after mixing using a Vortex IR mixer to ensuring adequate mix of samples for balanced solution. (See Appendix 2 point 23 for rack layout).

Running the ICP-MS

14) Basic prestart checks are required such as turning the argon supply on, ensuring all tubing is complete and necessary fluid levels are at the specified mark with waste drain empty.
15) Turn on the ICP-MS software to light the plasma a blue led should be lit showing that the machine is functional.
16) Run a standard performance check, if the sample successfully passes the instrumentation can be used to run the samples.

3.6 Data analysis

ISO data points were collected for each sample, and particle count using the MP Filtri CML4 particle counter. The given data provided from the MP Filtri oil sample were in particles per particle size class per 100ml (see table Appendix 3) to align sample results with ISO 4406 classification table (see table Appendix 4) it was required to convert the data from decilitre to millilitres through dividing the results by 100. The ISO code and contamination particle number operate in accordance with >4, >6, >14 the most impactful particle contamination size within oil systems. A recording of larger particles >21, >25, >38, >50 and >70 was recorded in the data document.

For the oil spectrometric analysis, the weight of each oil sample such as samples 1A and 1B were recorded at the start of the analysis process (see Appendix 5) to be used for the final calculations. During the automated sampling procedure, the ICP-MS captured and logged data for each of the targeted elements, producing an excel data sheet to summarise the results. To accurately interpret the findings, each data point must be calculated in relation to the original weight of the oil sample. Due to the initial 1:50 dilution of first sample and subsequent 1:50 dilution during digestion process it is necessary to convert the sample contamination level back to the original oil weight. This can be done through utilising the formula provided below, accounting for the element found in relation to original oil sample weight.

$$\text{Sample result x 50 x } \left(\frac{50}{weight\ of\ sample}\right)$$

$$0.017 \text{ x } 50 \text{ x } \left(\frac{50}{0.4638}\right)$$

$$0.85 \text{ x } \left(\frac{50}{0.4638}\right)$$

$$91.6\text{ppb}$$

$$91.6 \div 1000 = 0.0916 \text{ mg/kg}$$

The formula converts the data point for the original 50ml sample in line with the amount of contamination in the original sample weight and ensures that each individual data point has the same measurement unit for ease of contamination comparison.

3.7 Conclusion

The methodology used in this chapter assesses oil contamination levels in agricultural tractor hydraulic systems, with a focus on particle and element analysis co-working with one another. The process used to retrieve the data recorded involved the use of the MP Filtri CML4 particle contamination sampler in line with ISO 4406 to evaluate solid particle levels of contamination within the oil samples and ICP-MS for detailed element analysis of element findings and a change within the oil characteristics. The sampling procedure provided a detailed documentation of equipment, materials and protocols followed, as well as a description of how the implementation was set up and calibrated to ensure accuracy. Baseline readings were taken, and a standardised sampling method was followed across all tractor models to maintain consistency.

Chapter 4: Results

4.1 Introduction

This chapter presents the results of MP Filtri solid particle contamination analysis and ICP-MS chemical analysis of wear metal and additive elements. The results were processed in accordance with ISO 4406 and Analysis of Variance (ANOVA) was conducted.

4.2 Solid particle analysis oil contamination

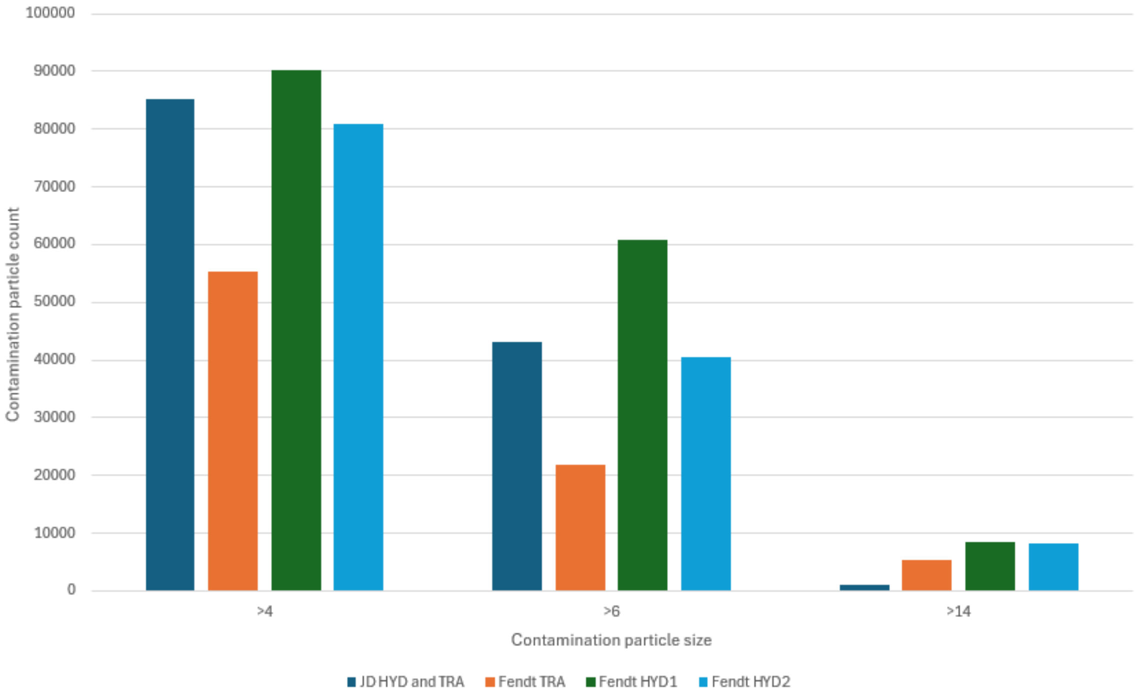
4.2.1 Results comparison with reference to ISO 4406

Mean, median and new clean oil particle contamination counts are shown in (Table 4) below for each individual tractor brand and oil type. Calculating the mean sample contamination particle size range >4, >6 and >14µm, recognised as the most damaging contaminant size in hydraulic and transmission oil, with (Figure 12) showing mean contamination particle count comparison. (Majdan *et al.*, 2019). This provides a contamination level relation to the mean sample particle contaminant abiding by ISO 4406 e.g. 24/23/17 for JD HYD and TRA. A difference was found in cleanliness of oil in Fendt transmission for particle count size >4 and >6. Lower particle contamination rate in particle size >14 was found in all brands and oil types. A clean new oil sample was analysed, to determine contamination level before use in the tractors. The particle counts and ISO 4406 code, to assess initial cleanliness and increase in contamination through operational use and wear (Table 4).

Table 4. Mean, median and clean oil brand comparison.

	Mean particle count			ISO 4406 code		
Brand and Oil type	>4	>6	>14	>4	>6	>14
JD HYD and TRA	85280	43243	1142	24	23	17
Fendt TRA	55217	21784	5309	23	22	20
Fendt HYD1	90282	60713	8352	24	23	21
Fendt HYD2	80995	40620	8255	24	22	20
	Median particle count			ISO 4406 code		
Brand and Oil type	>4	>6	>14	>4	>6	>14
JD HYD and TRA	88797	45319	1064	24	23	18
Fendt TRA	50932	16869	5177	23	21	20
Fendt HYD1	91536	63823	7827	24	23	21
Fendt HYD2	84692	38674	7985	24	22	20
	Clean oil particle count			ISO 4406 code		
Brand and Oil type	>4	>6	>14	>4	>6	>14
JD HYD and TRA	27444	3784	139	22	19	14
Fendt TRA	42265	8171	320	23	20	15
Fendt HYD1	47498	8392	126	23	20	14
Fendt HYD2	8385	2455	399	20	18	16

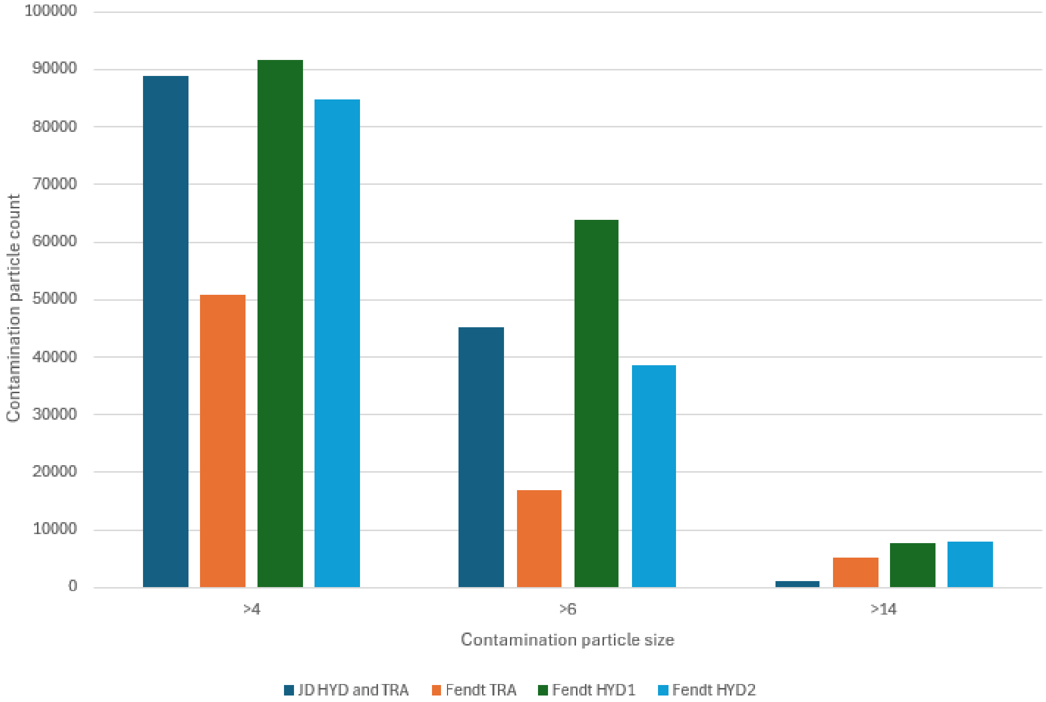
(Source: Author's Own, 2025)



(Source: Author's Own, 2025)

Figure 12. Mean particle contamination comparison for >4, >6 and 14.

A comparison of median particle contamination level is presented in Table 4 and Figure 13, alongside the corresponding ISO 4406 code. The values were calculated in relation to the data obtained by the CML4 calculating the sample median to identify whether there is skewness in data, following the conversion of results from decilitre to millilitres. A reduced amount of particle contamination can be seen in the Fendt TRA for particle size >4 and >6 with JD HYD and TRA and Fendt HYD demonstrating similar results. However, for particle size >14 JD HYD and TRA showed a lower particle contamination rate.

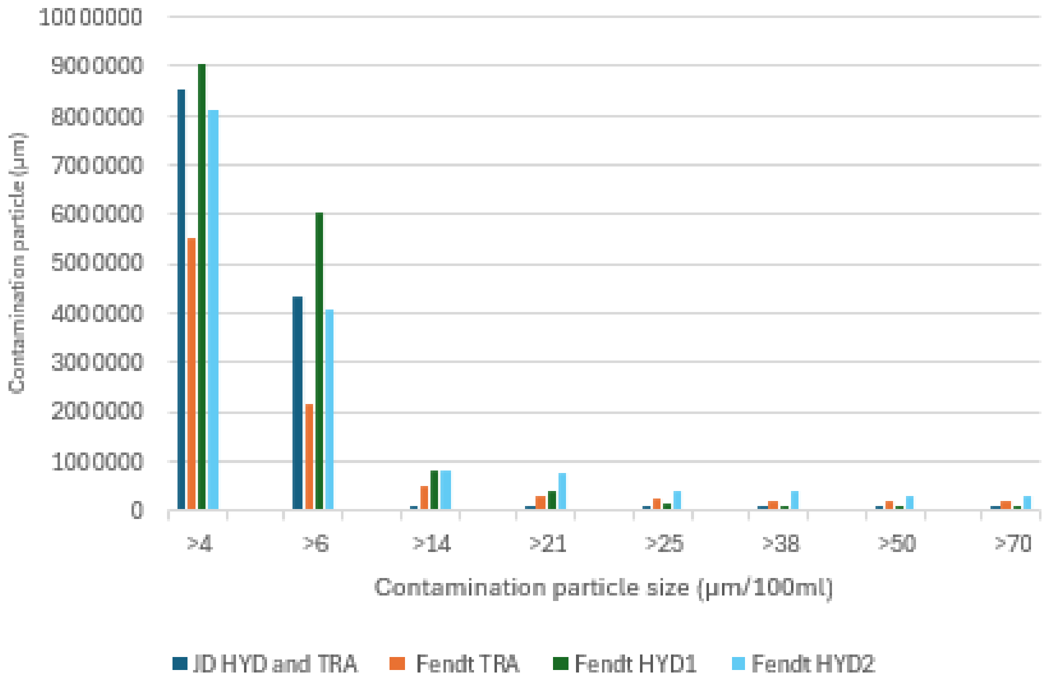


(Source: Author's Own, 2025)

Figure 13. Median particle contamination comparison for >4, >6 and 14.

4.2.2 Analysis of variation

Contamination particle counts are shown in Figure 14 below for the four brands and oil types, covering particle sizes >4 to >70µm. A repeated measurement of ANOVA followed by a Tukey test was carried out to confirm statistically significant difference in particle concentrations, across the different brands and oil type (see Table 7). The data highlights a significant difference in contamination levels between JD HYD and TRA, Fendt HYD 1 and 2 and Fendt TRA in contamination level. Fendt. JD has a 43% increase in contamination particle count in comparison to Fendt TRA. When comparing Fendt HYD1 to Fendt TRA there was an 79% increase in particle contamination in comparison to Fendt TRA. The comparison between Fendt TRA to Fendt HYD2 revealed 63% higher contamination level in Fendt HYD2.



(Source: Author's Own, 2025)

Figure 14. Dirt particle contamination comparison of full analysis range.

Table 5. Mean comparison contamination particle size >4 to >70 and significant (p<0.05).

Brand and Oil type	Mean	Classification	% difference
John Deere HYD and TRA	1671435	b	143
Fendt TRA	1170726	a	100
Fendt HYD1	2090374	b	179
Fendt HYD2	1905100	b	163

(Source: Author's Own, 2025)

A second ANOVA was conducted followed by Tukey test to confirm a statistically significant difference in particle concentrations across the different brands and oil type for particle sizes >4 to >14µm (Table 8). For each classification that are not significantly different they share the same letter. The data highlights a significant difference in contamination levels between JD HYD and TRA, Fendt HYD 1 and 2 and Fendt TRA in contamination level. Fendt. JD has a 58% increase in contamination particle count in comparison to Fendt TRA. When comparing Fendt HYD1 to Fendt TRA there was an 94% increase in particle contamination in comparison to Fendt TRA. The comparison between Fendt TRA to Fendt HYD2 revealed 58% higher contamination level in Fendt HYD2.

Table 6. Mean contamination comparison >4 to >14 combined and significance (p<0.05)

Brand and Oil type	Mean	Classification	% difference
John Deere HYD and TRA	4322157	b	158
Fendt TRA	2743647	a	100
Fendt HYD1	5311558	b	194
Fendt HYD2	4328998	b	158

(Source: Author's Own, 2025)

4.3 ICP-MS oil element comparison results to baseline sample

The analytic data obtained from the ICP-MS was converted from parts per billion (ppb) to milligrams per kilograms (mg/kg), enabling the calculation of the mean concentration of each chemical element per oil sample, in relation to the brand and oil type. ANOVA was conducted utilising the Statisty online application. Elements were grouped based on whether they showed a statistically significant difference in contamination level, at a 95% confidence level (Table 9), i.e. elements with a p-value below 0.05 were significant, above 0.05 not significant. (Table 10).

Table 7. Mean chemical element analysis of each brand and oil type significance (p<0.05)

Chemical Elements (mg/kg)	JD HYD and TRA Mean	Fendt TRA Mean	Fendt HYD1 Mean	Fendt HYD2 Mean	P-value
Significant					
Al	12.274	10.859	14.388	11.085	0.001
As	0.035	0.011	0.008	0.002	0.001
B	49.619	27.251	30.557	44.078	0.001
Ba	0.929	3.354	3.681	0.947	0.021
Ca	2838.136	3318.909	2542.317	2326.040	0.001
Cd	0.024	0.148	0.068	0.028	0.001
Cu	19.704	53.576	9.601	10.591	0.001
Fe	38.607	41.139	60.009	26.980	0.005
Mo	3.328	2.576	4.151	2.392	0.007
P	835.792	1130.287	838.402	694.408	0.001
Pb	3.270	4.127	2.697	2.601	0.009
S	3993.408	5098.656	3687.881	3404.684	0.001
Sn	24881.701	8858.092	4376.799	11635.631	0.001
Ti	2.044	2.319	1.806	1.691	0.001
Zn	1174.783	1311.189	1038.261	1055.543	0.001

(Source: Author's Own, 2025)

Table 8. Mean chemical element analysis of each brand and oil type non-significance (p>0.05)

Chemical Elements (mg/kg)	JD HYD and TRA Mean	Fendt TRA Mean	Fendt HYD1 Mean	Fendt HYD2 Mean	P-value
Non-Significant					
Cr	0.502	0.599	0.429	0.328	0.489
K	18.462	40.973	15.154	3.583	0.761
Mg	16.600	20.344	17.530	20.377	0.472
Mn	0.927	0.910	0.937	0.648	0.082
Na	36.282	99.173	33.291	21.540	0.737
Ni	0.244	0.597	0.345	0.171	0.360
Se	0.304	0.144	0.248	0.115	0.643
Si	4.289	7.999	0.0	0.0	0.365

(Source: Author's Own, 2025)

New clean oil samples were taken at each site location during the sampling process, creating a baseline comparison sample, that was ran through the ICP-MS analyser to determine the changes within the oil's chemical elements and were converted from ppb to mg/kg. Using the Statisty online application, the data was processed to calculate the mean concentration of each chemical element across oil types and brands (see Appendix 3). The p-values were calculated to determine both significant and non-significant contamination levels in the samples (Table 11 and 12).

Table 9. Mean chemical elements found in new clean oil baseline oil type significance (p<0.05).

Chemical Elements (mg/kg)	JD HYD and TRA Mean	Fendt TRA Mean	Fendt HYD1 Mean	Fendt HYD2 Mean	P-value
Significant					
B	109.31	12.60	15.86	5.59	0.001
Ba	0.01	5.25	15.43	0.13	0.001
Ca	3536.76	3162.77	2974.45	2420.44	0.001
Cd	0	0.22	0.19	0	0.001
Mg	10.04	28.99	21.87	11.85	0.001
Mo	0.19	2.71	5.63	3.18	0.01
P	486.90	1229.85	1179.24	413.25	0.001
Pb	0	0.78	0.61	0.15	0.001
S	5172.06	4859.88	3898.43	2479.72	0.006
Ti	2.37	1.98	1.91	1.65	0.007
Zn	1386.45	1201.64	1186.81	1053.73	0.003

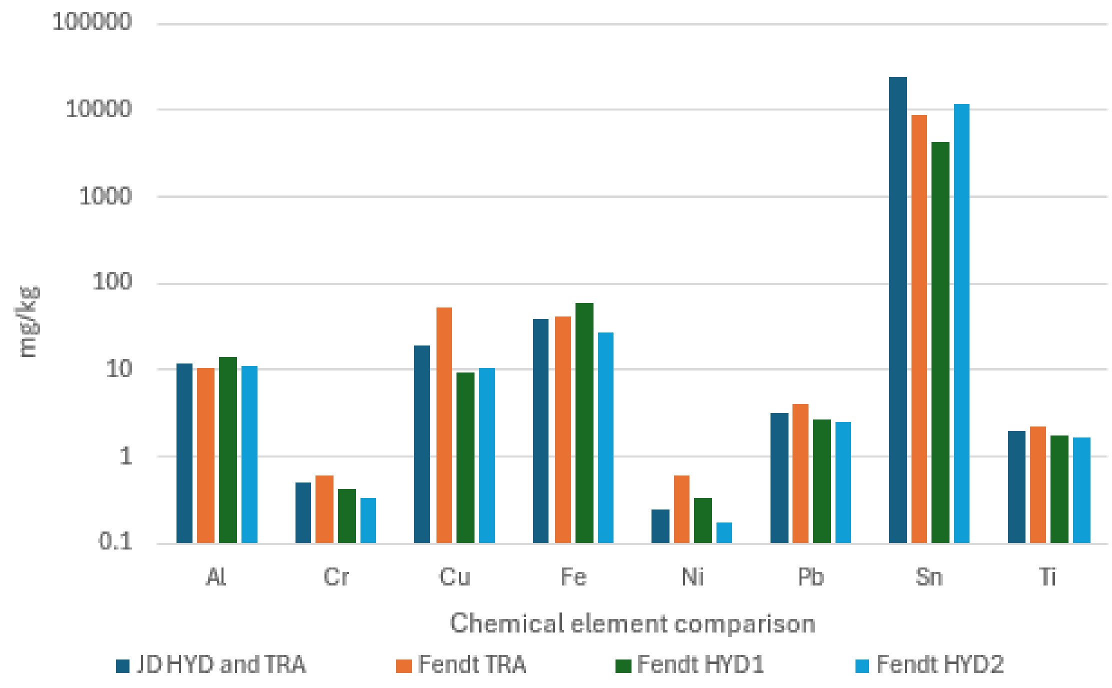
(Source: Author's Own, 2025)

Table 10. Mean chemical elements found in new clean oil baseline oil type non-significance (p>0.05).

Chemical Elements (mg/kg)	JD HYD and TRA Mean	Fendt TRA Mean	Fendt HYD1 Mean	Fendt HYD2 Mean	P-value
Non-Significant					
Al	8.98	8.51	9.86	11.76	0.076
As	0	0.02	0.02	0.01	0.342
Cr	0.08	0.08	0.06	0.08	0.956
Cu	0.03	0	0.10	0.16	0.323
Fe	1.13	1.05	3.33	2.78	0.134
K	0	0	0	0	N/A
Mn	0	0.09	0.11	0	0.081
Na	5.07	1.99	1.59	0	0.201
Ni	0.04	0.04	0.02	0.01	0.225
Se	0	0.22	0.39	0	0.230
Si	0	0	0	0	N/A
Sn	0	0	0	0	N/A

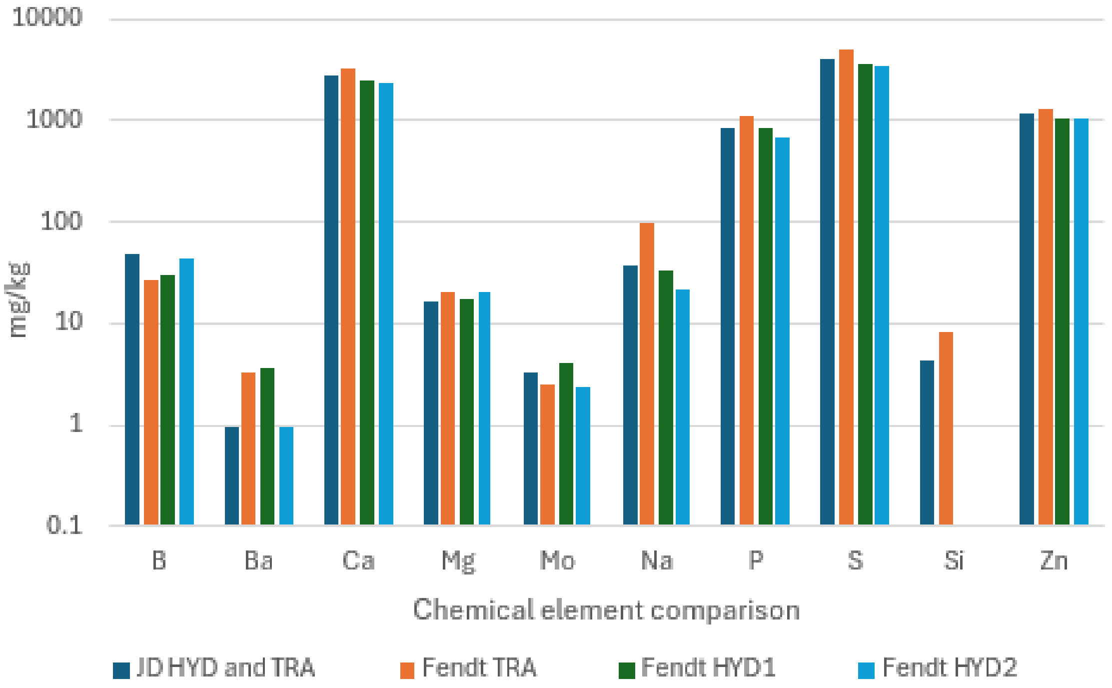
(Source: Author's Own, 2025)

Grouping the wear element and additives allowed for a comparison highlighting key increase in element contamination within the oil, to identify correlations within internal transmission and hydraulic operating components. (Figure 15) demonstrates a significant increase in contaminant in the contaminated oil of wear component and (Figure 16) shows the levels of additive chemical element comparison.



(Source: Author's Own, 2025)

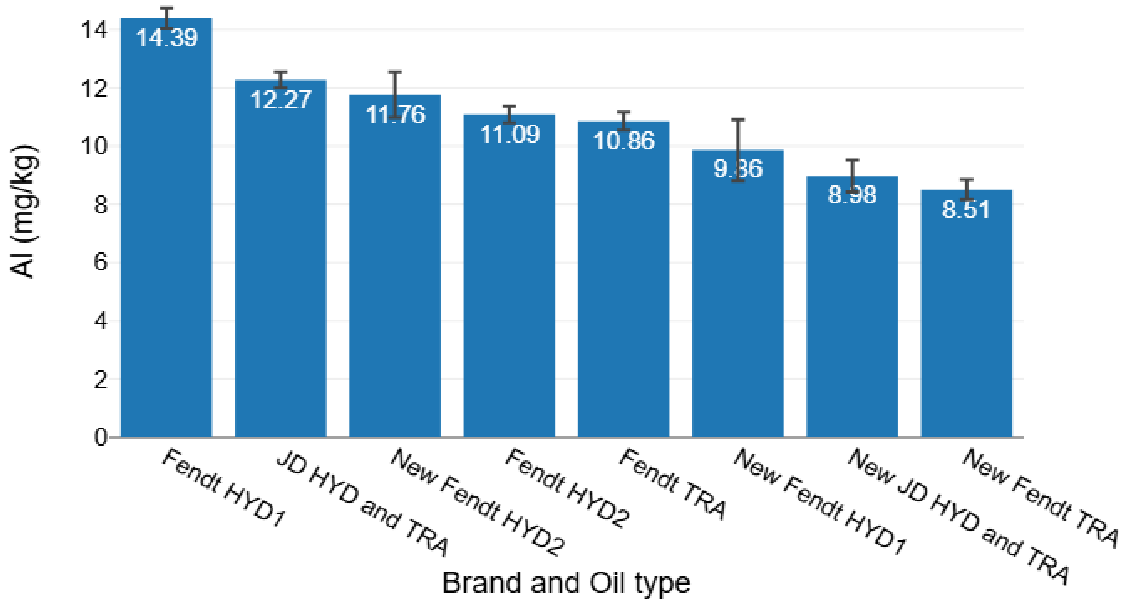
Figure 15. Chemical elements mean comparison of increase contaminants of wear components in the oil.



(Source: Author's Own, 2025)

Figure 16. Chemical element analysis comparison of additives changes in the new clean oil.

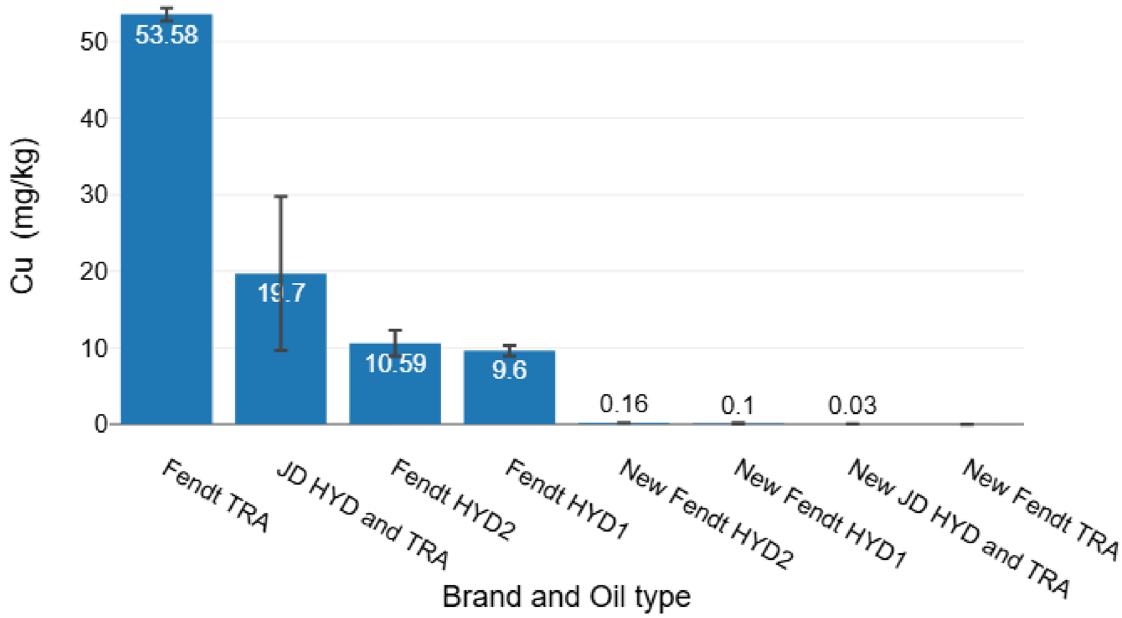
Four key wearing components Al, Cu, Fe and Sn can be compared to the baseline clean oil sample following findings in (Figure 15) of increase contaminant level. Additionally, (Figure 16) demonstrates the highest concentrations of additive elements such as Ca, S and Zn. Identifying key chemical elements that are commonly found in contaminated oil, through internal wearing components such as Al, that's commonly found in transmission and hydraulic oil from cylinders, pump bearings and component housing of working components (Indiana, 2020). This is shown in figure 17 with an increase in AL in comparison to the baseline clean oil.



(Source: Author's Own, 2025)

Figure 17.Mean level of Al in treatments, error bar shows standard error

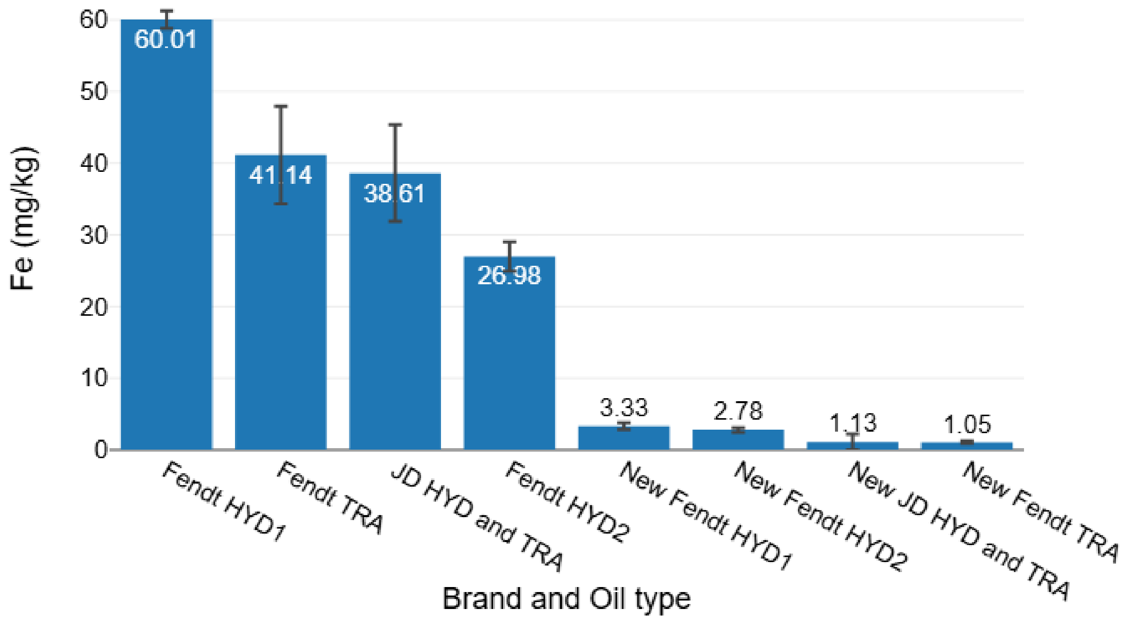
Copper (Cu) is often found in internal components such as bushes, bearings, clutches and oil coolers (Indiana, 2020), leading to the possible cause of increased contamination across all oil sample (Figure 18) with a significant increase demonstrated in Fendt TRA and JD.



(Source: Author's Own, 2025)

Figure 18. Mean level of Cu in treatments, error bar shows standard error

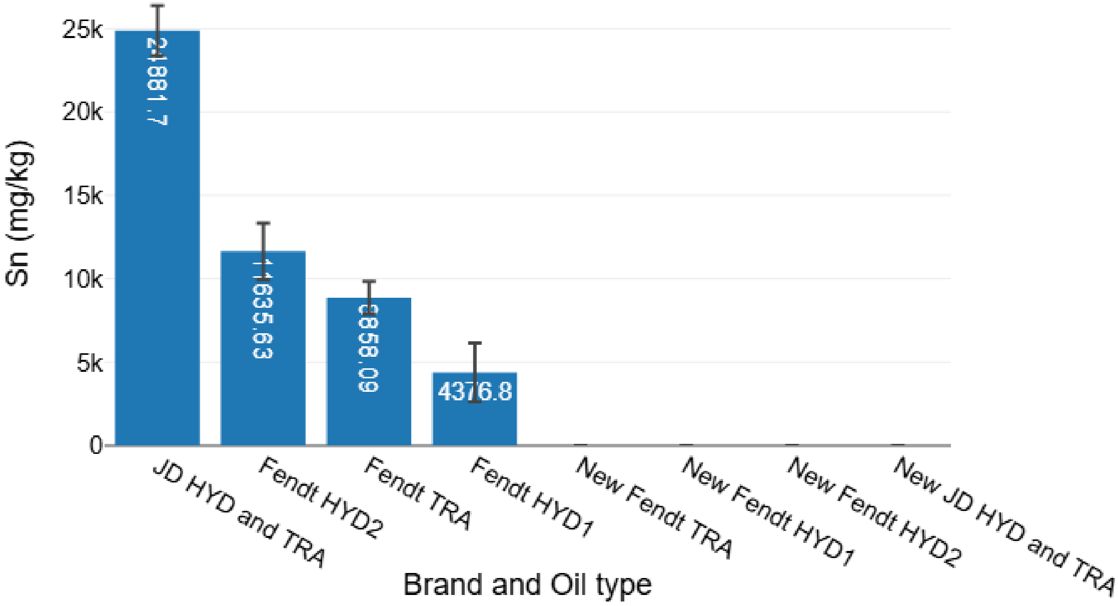
Iron (Fe) is often found as a key contaminant in hydraulic and transmission oil, due to the range of operating component such as pumps, gears and bearings leading to increased contamination through wear and breakage (Indiana, 2020). This is clearly shown in (Figure 19) in Fendt hydraulic.



(Source: Author's Own, 2025)

Figure 19. Mean level of Fe in treatments, error bar shows standard error.

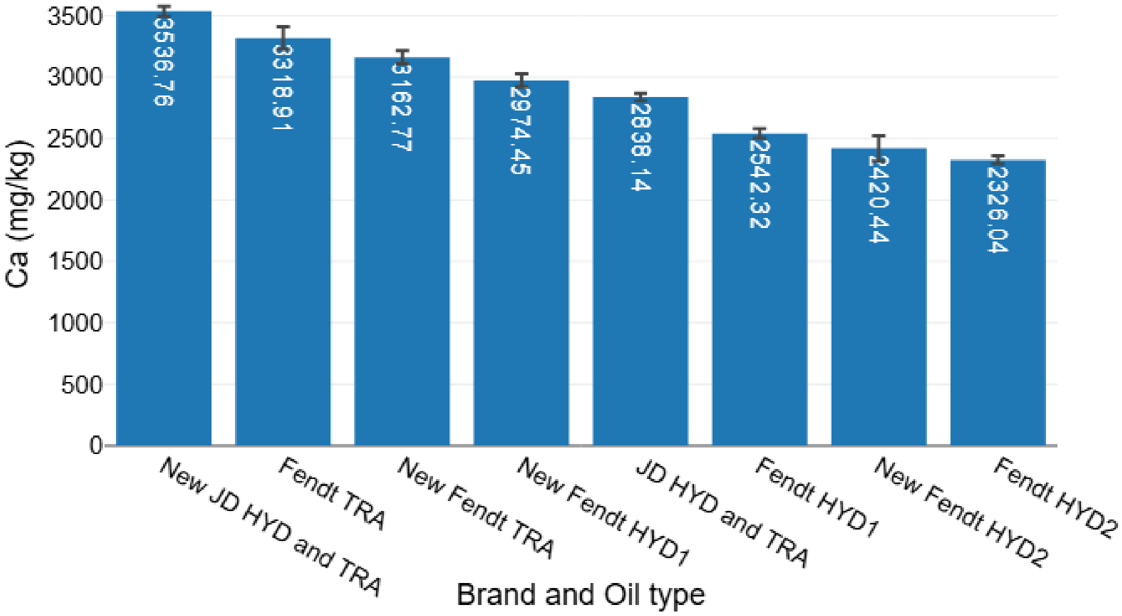
Contamination in oil can occur from working bearings, gear or cylinder parts within the systems component design (Indiana, 2020), (Figure 20) shows an increase in contamination level across all samples in comparison to clean oil that had no Sn presence.



(Source: Author's Own, 2025)

Figure 20. Mean level of Sn in treatments, error bar shows standard error.

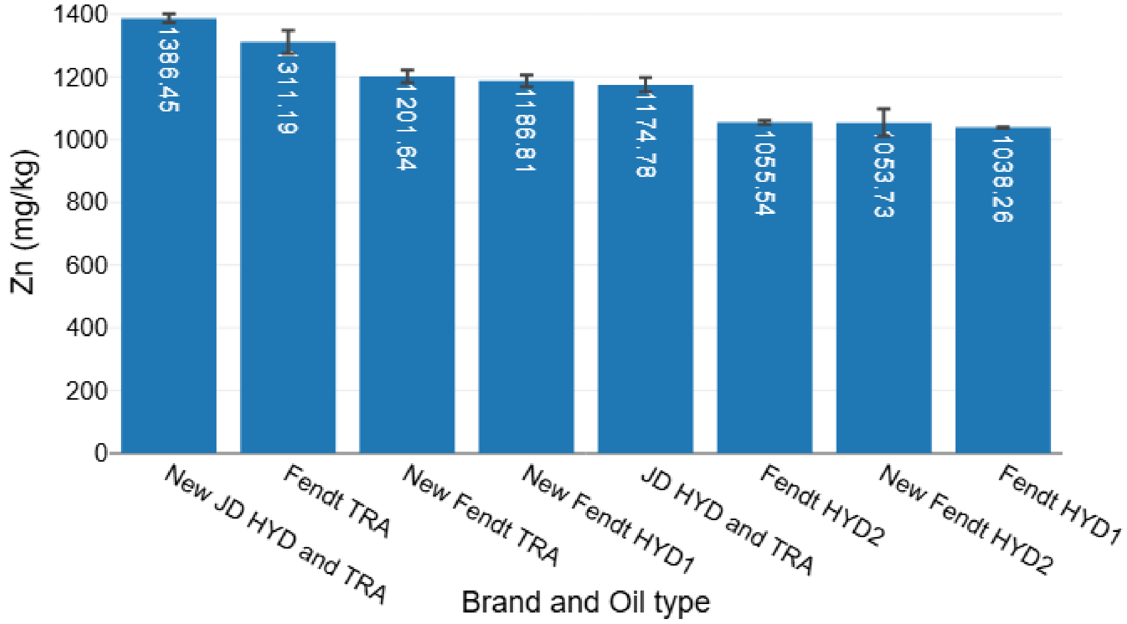
Additives in oil can have a positive and a negative effect, (Figure 21) shows a high level of Calcium (Ca) throughout the oil samples, especially in new JD. It can be identified in dust, rubber and hard water and is added as a detergent (Indiana, 2020), with a clear reduction of 20% from operational use in the contaminated oil of JD.



(Source: Author's Own, 2025)

Figure 21. Mean level of Ca in treatments, error bar shows standard error.

Zinc (Zn) is a recognised additive added to oils as a anti wear additive. It is commonly used as a zinc coating for components such as valves and fittings (Indiana, 2020). (Figure 22) demonstrates a clear trace add in clean JD with a reduction through degradation of the additive shown in contaminated JD.



(Source: Author's Own, 2025)

Figure 22. Mean level of Zn in treatments, error bar shows standard error.

Chapter 5: Discussion and Further work

5.1 General findings

Throughout the data collection process, a focus on particle and element analysis provided an insight into oil contamination in tractor transmission and hydraulics, in accordance with ISO 4406. Testing showed carbon (C) commonly found in brakes and clutches recognised as contamination in the oil (Yevtushenko *et al.*, 2022) was not included in the ICP-MS analysis.

5.2 Results evaluation

During the sampling and site selection process, accessibility to Fendt manufactured tractors was limited, with their inventory consisting of older tractors with higher operating hours. In contrast the JD site had newer models, with lower operating hours. Experimental sampling was carried out with two treatments type of hydraulic oil differing in their service practices for Fent tractors, caused concern with the possibility of skewness in the data groups. However, the Tukey test demonstrated that there was no significant difference between the two hydraulic oil samples within contamination levels (see table's 7 and 8, 4.2.2 Analysis of variant)

5.2.1 ISO classification particle size and count

A reduction in oil contamination level was identified within the separate transmission on the Fendt tractors in comparison to the John Deere. This demonstrated a lower ISO 4406 rating for Fendt.

A significant difference between the oils was identified in terms of all particles >4 to >70um. It is apparent that the Fendt transmission is the cleanest and that Fendt hydraulic 1 contained the highest contamination level, as anticipated from maintenance intervals (see section 3.3; Majdan *et al.*, 2019). John Deere oil had the lowest contamination level in particle size >14, this result was unexpected and could have been due to the filtration specification grade of manufacturer collecting the larger particle size in filters.

The new baseline oil samples were analysed to identify contamination level and accordance with the ISO 4406 level of acceptability. Analysis identified a higher overall ISO 4406 grading than acceptable. Demonstrating that there is prior contamination within the supplied virgin oil sampled, which agreed with Des-Case (2019) that new oil can usually contain between 2 to 20 times the number of particles accepted by most equipment. Reason being the process of oil from refinery to point of use in equipment through the transfer and storage process (see Appendix 7). However, there was still a clear indication of increased contamination across all samples from internal wearing components and externally sourced debris.

5.2.2 Chemical elements

The mean of each element was determined based on oil type and manufacturer design. This analytical approach identified a significant difference in the element concentration within the oils, supporting the particle count contamination findings recorded by the CML4. This allowed for the identification of metallic increase associated with specific wearing of operational components within the vehicle configuration. Additionally, the analysis assessed changes to the elements in relation to additives by comparing used oils to their clean counterparts.

A significance test revealed that 15 elements showed significant differences compared to clean oil out of the 23 elements looked at. In contrast, only 12 samples showed significance in the clean counterparts, indicating an increased presence of externally introduced contaminants and wear of additives in the oil.

Nwosu *et al*. (2008) states that Al, Cu, and Fe are some of the most critical wear particles found in lubricating oil. This agrees with Latip *et al*. (2016) who stated in their investigation that Al, Cu, and Fe was found as the most significant wear element, supporting the findings reflected by the ICP-MS data, with significant increases in Cu and Fe in comparison to baseline clean oil samples analysed.

The concentration of each chemical element increased in the oil, which agrees with Nwosu *et al*. (2008) who stated in their investigation that there is generally an increase in wear metal concentrations that are not related to additive induced behaviour, which relates closely to the findings in the oil samples across the experiment. There was a high trace of tin (Sn) element found throughout the contaminated samples, especially in the John Deere reservoir, an increase of 24,881mg/kg in the samples. Sn was not used as an additional additive with no trace in the baseline new clean oil samples, indicating that contamination is being introduced by a foreign object. Tin is often found in bearings and bronze alloys that are found in bushings and washers (Indiana, 2021), they are typically monitored in line with copper and lead levels for early signs of component degradation.

Adopting a separate reservoir design offers a clear advantage, however it is clear there will always be traces of contamination within the oil. This may originate from pre-existing impurities within the new virgin oil or from wearing components and externally sourced debris. Operator management and care when changing and connecting equipment plays a vital role in cleanliness through closing the dust caps and cleaning hose end before attaching, reducing entry of exterior contaminants.

ICP-MS analysis highlighted where each increase in element wear was most apparent, with a significant increase of Cu in Fendt TRA from working bushes and bearings. Second highest levels Cu was JD HYD and TRA with significant reduced amount of Cu in Fendt HYD 1 and 2 showing Cu contamination is more prone in the transmission. Whereas a significant increase of iron (Fe) element could be found in the Fendt HYD 1 sample, indicating contamination from external waring components and attachments. This shows a benefit for both systems through having separate reservoirs, reducing wear filings from flowing through externally attached auxiliary and reduced cross contamination entering the transmission oil, from left residual in cylinders and hoses, changing the oils original state and additive performance.

5.3 Recommendations for further work

For a longer study run a repeat analysis, reducing the number of samples per site to 5, but increasing the number of locations, comparing different farm types such as arable, beef and dairy. Adjustment to sample volumes per tractor for particle analysis, by performing three replicates, using the average result to represent each data group. Enhance sample consistency through adding a connection point to a warmup hose to collect 100ml every 30 seconds, once the system reaches the appropriate temperature, for a 500ml sample.

Run a repeat study to validate the methodology used for the ICP-MS feed process that was followed for oil analysis against other standards and regulations (Olsen *et al.*, 1995). For example, evaluating samples using the reference criteria provided by approved oil spectrometric analysis including the carbon (C) chemical element in oil. Adapting a scale of percentage change to the additives within the oil, to observe whether the chemical elements increase or decreases, with further research identifying the cause and effect on component wear.

Chapter 6: Conclusion

The design of John Deere tractors consists of a combined hydraulic and transmission oil reservoir, whereas Fendt have a separate transmission system with a dedicated secondary hydraulic reservoir. Oil contamination levels were monitored using MP Filtr CML4 particle counting technology. PerkinElmer Nexion 2000 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to identify and quantify metallic elements within the oil.

Oil samples were extracted under controlled conditions ensuring accuracy and consistency across both brands. The MP Filtri CML4 analysis revealed a significant difference in particle size of >4 to >6µm contamination levels, ISO 4406 indicates this as a range for susceptible system sealing integrity, component wear and filtration. Fendt transmission was cleanest (ISO 23/21/20) but the separate hydraulic tank Fendt HYD2 (24/22/20) was comparable with John Deere (24/23/18). A larger margin between Fendt HYD1 (24/23/21), reflective of maintenance practices followed.

ICP-MS provided an insight of increased levels of wear metals in the contaminated oil, in comparison to new clean baseline oil. Identifying wear metals such as aluminium, copper and iron, an indication of critical wear in components such as pumps, gears and bearings. Thereby increasing the contamination levels of the hydraulic and transmission systems whilst monitoring key additive element change.

Al, Cu, Fe and Sn were found to be the most significant wear elements, demonstrated in the ICP-MS data. The highest trace of both Al and Fe was found in the Fendt HYD1, followed by the sperate and combined transmission reservoir. A significant increase of Cu was found in the Fendt TRA, especially considering there was no trace in new Fendt TRA oil. A major increase in Sn element trace was found across all reservoirs, with an increase of 24882mg/kg in the combined JD HYD and TRA, with no previous Sn trace in new oil. JD HYD and TRA found the highest reduction in Ca additive amount, with a similar reduction effect in Zn. A reduction of Zn was also identified in Fendt HYD1 and no change in Fendt HYD 2.

The oil sampling technique acquired can effectively characterise the internal condition and design efficiency of hydraulic and transmission systems. The methodology developed provided a reliable framework for future studies across additional brands to identify contamination levels and traces of wear metals.

Recommendations beyond this work include focusing on additional brands such as New Holland, Claas and John Deere that have similar combined reservoirs, JCB and Fendt both run separate hydraulic reservoirs that can warrant further investigation.

References

AGCO (2014) *Fendt Special Hyd 46 Hydraulic Oil*. Available at: https://uklubricants.agcoparts.com/downloads/fendt-tds/Fendt_Special_Hyd_46.pdf (Accessed: 11 May 2025).

AGCO (2015) *AGCO Parts Multipurpose Tractor Oil 15W-30*. Available at: https://uklubricants.agcoparts.com/downloads/agco-tds/AP_Multipurpose_Tractor_Oil_15W-30.pdf (Accessed: 11 May 2025).

AGCO (2017) *AGCO FENDT 700 VARIO S4 SERIES WORKSHOP SERVICE MANUAL Pdf Download*, *ManualsLib*. Available at: https://www.manualslib.com/manual/1952539/Agco-Fendt-700-Vario-S4-Series.html#manual (Accessed: 11 May 2025).

AGCO (2019) *Fendt Extra Trans 10W-40 Transmission STOU*. Available at: https://uklubricants.agcoparts.com/downloads/fendt-extra-trans-10w40---sept-2019.pdf (Accessed: 11 May 2025).

AGCO (2025) *Fendt 700 Vario Gen7*. Available at: https://dam.agcocorp.com/content/dam/multisite/fendt/marketing/multi-region/documents/marketing-material/brochures/tractors/700-vario-gen7/en/Fendt700VarioGen7_EN_web.pdf (Accessed: 11 May 2025).

Ahmed, N.S. and Nassar, A.M. (2011) 'Lubricating Oil Additives', *Tribology - Lubricants and Lubrication*. Available at: https://www.researchgate.net/profile/Nehal-Ahmed-3/publication/221918100_Lubricating_Oil_Additives/links/0f3175309d9e73c79e000000/Lubricating-Oil-Additives.pdf

Aleksander Yevtushenko, Piotr Grzes, Aleksander Ilyushenko and Andrey Liashok (2022) 'An Effect of a Carbon-Containing Additive in the Structure of a Friction Material on Temperature of the Wet Clutch Disc', *Materials*, 15(2), pp. 464–464. Available at: https://www.mdpi.com/1996-1944/15/2/464

DES-CASE (2019) *CRACKING THE ISO CODE TO LUBRICANT CLEANLINESS 2*. Available at: https://www.descase.com/wp-content/uploads/2019/11/WP1703_ISO-Cleanliness-Whitepaper.pdf.

Ferrari, C., Marani, P. and Ghorpade, K. (2015) *CFD MODELING OF LUBRICATION SYSTEM IN AGRICULTURAL POWER SPLIT TRANSMISSION CFD MODELING OF LUBRICATION SYSTEM IN AGRICULTURAL POWER SPLIT TRANSMISSION*. Available at: https://www.researchgate.net/profile/Cristian-Ferrari-2/publication/302925238_CFD_MODELING_OF_LUBRICATION_SYSTEM_IN_AGRICULTURAL_POWER_SPLIT_TRANSMISSION/links/5a1ee71ea6fdccc6b7f8fa58/CFD-MODELING-OF-LUBRICATION-SYSTEM-IN-AGRICULTURAL-POWER-SPLIT-TRANSMISSION.pdf (Accessed: 11 May 2025).

Galtech (2018) *CATALOGO TECNICO -TECHNICAL CATALOGUE Divisori di flusso Flow dividers*. Available at: https://www.flowfitonline.com/uploads/PDFproducts/2sf1.pdf (Accessed: 11 May 2025).

Health Safety Executive (2015) *Emergency Response / Spill Control*, *Hse.gov.uk*. Available at: https://www.hse.gov.uk/comah/sragtech/techmeasspill.htm

Hertzog, M.A. (2008) 'Considerations in Determining Sample Size for Pilot Studies', *Research in Nursing & Health*, 31(2), pp. 180–191. Available at: https://onlinelibrary.wiley.com/doi/pdf/10.1002/nur.20247

Hill, P. (2025) *Dealers feel the heat as kit sales plummet and costs rocket - Farmers Weekly*, *Farmers Weekly*. Available at: https://www.fwi.co.uk/machinery/dealers-feel-the-heat-as-kit-sales-plummet-and-costs-rocket (Accessed: 11 May 2025).

Horne, S. (2023) *Steep price rises put focus on machinery costs*, *Farmers Weekly*. Available at: https://www.fwi.co.uk/business/markets-and-trends/input-prices/steep-price-rises-put-focus-on-machinery-costs.

HSE (2022) *Personal Protective Equipment (PPE) at Work Regulations from 6 April 2022*, *www.hse.gov.uk*. Health and Safety Executive. Available at: https://www.hse.gov.uk/pubns/law.pdf

Hujo, L., Nosian, J., Zastempowski, M., Kosiba, J., Kaszkowiak, J. and Michalides, M. (2021) 'Laboratory tests of the hydraulic pump operating load with monitoring of changes in the physical properties', *Measurement and Control*, 54(3-4), pp. 243–251. Available at: https://journals.sagepub.com/doi/pdf/10.1177/0020294020983385

Indiana, A. (2020) *Oil Cleanliness & Contamination Reference POCKET GUIDE*. Available at: https://mrhydraulics.co.uk/wp-content/uploads/2021/02/oil-cleanliness-contamination-pocket-guide.pdf (Accessed: 11 May 2025).

ISO 4406 (2021) *Hydraulic fluid power -Fluids -Method for coding the level of contamination by solid particles Transmissions hydrauliques -Fluides -Méthode de codification du niveau de pollution particulaire solide*. Switzerland : IS0. Available at: https://cdn.standards.iteh.ai/samples/79716/d9e67bb574834f389e27d374af881811/ISO-4406-2021.pdf.

John Deere, 2013. Operating The Transmission. Available at: http://manuals.deere.com/omview/OMAR276030_19/OURX935,000013E_19_20101108.html

John Deere (2020) *Hy-Gard™ Hydraulic and Transmission Oil*. Available at: https://www.deere.com.au/assets/pdfs/common/parts-and-service/parts/aunz-hy-gard-brochure.pdf (Accessed: 11 May 2025).

John Deere (2022) *REPLACEMENT PARTS GUIDE 6R Final Tier 4 (FT4/Stage V) MY22 Series Row Tractors-6R 145, 6R 175, 6R 195, 6R 215*. Available at: https://www.deere.com/assets/pdfs/common/qrg/6r-ft4stage-6r145-6r175-6r195-6r215.pdf (Accessed: 11 May 2025).

John Deere (2025) *6r Tractor Brochure, Widen.net*. Available at: https://johndeere.widen.net/view/pdf/n7to5qxvdf/yy2514141-6r-tractor-brochure-en.pdf (Accessed: 11 May 2025).

Kosiba, J., Vozarova, V. and Petrović, A. (2018) *Monitoring oil degradation during operating tests*. Available at: https://www.researchgate.net/profile/Jan-Kosiba/publication/311259869_Monitoring_oil_degradation_during_operating_tests/links/5afe8458aca272b5d84ab101/Monitoring-oil-degradation-during-operating-tests.pdf (Accessed: 11 May 2025).

Latip, S., Kasolang, S., Michael, Z., Naufal, A., Mekanikal, F., Teknologi, U., Johor, M., Kampus, P., Gudang, J., Purnama, S., Alam, Masai, Shah, M., Alam, S., Selangor, M. and Akademia Baru, P. (2016) 'Oil analysis of used Perodua automatic transmission fluid (ATF-3) using spectrometric technique Akademia Baru', *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences Journal homepage Open Access Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 28(1), pp. 17–25. Available at: https://www.akademiabaru.com/doc/ARFMTSV28_N1_P17_25.pdf (Accessed: 11 May 2025).

Máchal, P., Majdan, R., Tkáč, Z., Stančík, B., Abrahám, R., Štulajter, I., Ševčík, P. and Rášo, M. (2013) 'Design and verification of additional filtration for the application of ecological transmission and hydraulic fluids in tractors', *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 61(5), pp. 1305–1311. Available at: https://d1wqtxts1xzle7.cloudfront.net/74521427/actaun_2013061051305-libre.pdf?1636628402=&response-content-disposition=inline%3B+filename%3DDesign_and_verification_of_additional_fi.pdf&Expires=1746989885&Signature=Qs5FRCsVyqcmQn2Zzd2m20h5aji7B5SseSheXcEEFHoq~wBgqnNe6LoyShWILnOh5Oyy3a7CMZVO~PtjTIGbg7x557-fywmGuW4ED89NNd96624pJlrvfkgvP4opsijhkgWjodqtMC7mr4o0ZUlV~T9MF-yIs48IRqN5nc83NyKbr7zIVUlPRopk2S816vpiWouiiw31wt9-Yuf5wd2HELVzUeEcyH0aLdRkaZR4RSFHCimqG24GPiRwaNNJXrfZDAZkrBLetFyJC8E7fG3Sy2so4p9OatAPy5Lxm-0yIzsX9uRncKxU3CggSoZjXgMsWC-GtT4pPNQqY2Bn5WujaA__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

MAČUŽIĆ, I. and JEREMIĆ, B. (2004) 'Proactive Approach to Oil Maintenance Strategy', *Tribology in industry,* 26, pp. 27–31. Available at: http://www.tribology.fink.rs/journals/2004/1-2/5.pdf

Majdan, R., Abrah, R., Uhrinov, D. and Nosian, J. (2019) 'Contamination of transmission and hydraulic oils in agricultural tractors and proposal of by-pass filtration system', *Agronomy Research*, 17(S1), pp. 1107–1122. Available at: https://dspace.emu.ee/server/api/core/bitstreams/56789e78-b059-4317-8211-2692bb65e37f/content

Majdan, R., Tkáč, Z., Abrahám, R., Kollárová, K., Vitázek, I. and Halenár, M. (2016) 'Filtration Systems Design for Universal Oils in Agricultural Tractors', *Tribology in Industry*, 39(4), pp. 547–558. Available at: https://agronomy.emu.ee/wp-content/uploads/2016/05/Vol14_nr4_Majdan.pdf

Maple Lane Farm Service, 2025. Service Interval Hours. Available at: https://maplelanefarmservice.ca/resources/links/Service_Intervals_Fendt_Gold_Star_Customer_Care.pdf?srsltid=AfmBOopSoHBIf2sycjTQ_pAbNHB74eTVn7fmomX7O3JEoc1yBlDah4ea (Accessed: 11 May 2025).

Marko, O., Mitar, J. and Velibor, K. (2020) *Applying contamination control for improved prognostics and health management of hydraulic systems*. Available at: https://orbilu.uni.lu/bitstream/10993/63701/1/Orosnjak%20et%20al%20-%20Comadem%20paper%20-%20Preprint.pdf (Accessed: 11 May 2025).

MP Filtri (2021) *FLUID CONDITION AND FILTRATION HANDBOOK Manual of analysis and comparison photographs*. Available at: https://www.mpfiltri.com/FilesProdotti/HANDBKENA520.pdf (Accessed: 11 May 2025).

MP Filtri (2022) *CONTAMINATION CONTROL SOLUTIONS*. Available at: https://www.mpfiltri.com/FilesProdotti/QB3xWs_CCSEN.pdf (Accessed: 11 May 2025).

Ng, F., Harding, J.A. and Glass, J. (2017) 'Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring', *Mechanical Systems and Signal Processing*, 83, pp. 176–193. Available at: https://www.sciencedirect.com/science/article/pii/S0888327016301881?via%3Dihub

Nwosu, F.O., Iromidayo Olu-Owolabi, B., Adebowale, K.O. and Leke, L. (2008) *Comparative Investigation of Wear Metals in Virgin and Used Lubricant Oils*. Available at: https://d1wqtxts1xzle7.cloudfront.net/86610033/TAET_2138-43o-libre.pdf?1653753152=&response-content-disposition=inline%3B+filename%3DComparative_Investigation_of_Wear_Metals.pdf&Expires=1747008217&Signature=F8C-bCRZP4AzAX0ab2rJ2ilQLW-2JS5JlZPR4KCZuTdDx4w5vOnAZcYY09eAcA9d~YgHohUbRx~zyJNAD0oijwjnUhXAAgtCw5z2IWW3RsYUNZTxvQ9fmBtMY13AS1ZPbanm9tVAUdIAOp1nFYueVRXtpeoS6hpPwBV1sWDMmNCRnTqM9XH-BullnevTrf~qNnsshQZXmYRAxzCzCDO71~3hY7NBD3dPF3o2EnoQPlXBYWraLurkf9Rij1dPlHwsv-UW7n25miq~~AGF33LdJNDXr0~9EtPh67nHnmP1wVTWVRkfWfrcqlL0SNa0SUWKmzf6ZaSz3TBQ5lM1dUXV2Q__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA (Accessed: 11 May 2025).

O'Brien, J.A., 1983. Lubricating oil additives. In: E.R. Booser, ed. *CRC Handbook of Lubrication*. Vol. 2. Boca Raton, FL: CRC Press, pp.301–315.

Obasi, A. and Udeagbara, S. (2014) 'Effect of Additives on the Performance of Engine Oil', *Online) International Journal of Engineering and Technology Research*, 2(9), pp. 2327-0349. Available at: http://www.ijeatr.org/IJEATR_Vol.%202,%20No.%209,%20October%202014/Effect%20of%20Additives.pdf (Accessed: 11 May 2025).

Olsen, S.D., Filby, R.H., Brekke, T. and Isaksen, G.H. (1995) 'Determination of trace elements in petroleum exploration samples by inductively coupled plasma mass spectrometry and instrumental neutron activation analysis', *The Analyst*, 120(5), p. 1379. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=acb3cef41eda1a6b3d675268934685d787b7e751

Pabsetti, P., Murty, R.S.V.N., Bhoje, J., Mathew, S., Rahul, K. and Feroskhan, M., (2023) 'Performance of hydraulic oils and its additives in fluid power system: A review', *IOP Conference Series Earth and Environmental Science*, 1161(1), pp. 012009–012009. Available at: https://iopscience.iop.org/article/10.1088/1755-1315/1161/1/012009/pdf

Puhan, D. (2020) 'Lubricant and lubricant additives', in *Tribology in Materials and Manufacturing-Wear, Friction and Lubrication*, Chapter 9. pp. 169-201.

Ramesh, D., Thirumoorthy, A., Kandasamy, K. and Suresh, S. (2019) '94 100 Article ID: IJPTM_10 2 14 -, _0 _0 Comportment Puller', *International Journal of Production Technology and Management (IJPTM)*, 10(2), pp. 94–100. Available at: https://d1wqtxts1xzle7.cloudfront.net/67903089/IJPTM_10_02_014-libre.pdf?1625644173=&response-content-disposition=inline%3B+filename%3DHYDRAULIC_COMPORTMENT_PULLER.pdf&Expires=1746977700&Signature=DFfNvbjOo6lGV34~Naylsc8ze7b-rES6renUTv3nZs2QbPrDJsl8YqBWj3UR9naXMy1bKsEHzuTNz6Ndzsw12P9bQe3OVjsCdKUH6uaqb1H7Qy-~Mxkiy~FdpyXkvZWp2XpUE034GkqTsli8XWEpWtnZICzUqTHJaH98NEvi5KRNJlOnq8y2DrX~BQCIdeTIXFHrLCkgTDsV3uksv714OEG9fMYiOUliDlDMIrZK94oQzntSlhnzs~1TqWiBqPjhRTUlfw06FPCbaZhTCNbHlCRF-D-YDQYqWid~FqpwkT0ObJl~8nUM5wqFwnQVoQmUGGD7ji8Vbh1MUIm46~82Pw__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA (Accessed: 11 May 2025).

Roxroth (2017) *Solenoid operated valves direct acting spool 5-way 3-position Common cavity, Size 10*. Available at: https://apps.boschrexroth.com/products/compact-hydraulics/ch-catalog/pdf/OD53X54KK2Y00_RE18324-65.pdf (Accessed: 11 May 2025).

Rexroth (2013) Rexroth Oil Cleanliness Booklet 2. Available at: https://hydraulique-martin.com/wp-content/uploads/2021/02/Bosch-Oil-Cleanliness-Booklet.pdf (Accessed: 11 May 2025).

Renius, K. T. (2019) 'Tractor and implement', in *Fundamentals of Tractor Design*. [Online]. Switzerland: Springer International Publishing AG. pp. 217–260.

Șcheaua, D. (2024) *Fluid Contamination Aspects Due to Hydraulic System Operation*. Available at: https://hidraulica.fluidas.ro/2024/nr4/29-39.pdf (Accessed: 11 May 2025).

Schneider, M.P. (2006) 'Plant-oil-based lubricants and hydraulic fluids', *Journal of the Science of Food and Agriculture*, 86(12), pp. 1769–1780. Available at: https://scijournals.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/jsfa.2559

Shekokar, S., Shekokar, R., Khachne, K., Choudhari, G., Choudhari, C. and Wadhe, S. (2025) *'Multioperation Hydraulic Press Machine'*, *Journal of Progressive Research (FEJOPR) FuturEdge: Journal of Progressive Research*. FEJOPR. Available at: https://coemalkapur.ac.in/engg/uploads/copy-1738126445-10.pdf (Accessed: 11 March 2025).

Singh[1], D. and Suhane[1], A. (2014) 'Modification of Hydraulic System of Tractor for Removal of Magnetic Particles from Hydraulic Oil', *International Journal of Engineering Research*, 10(5), pp. 56–60. Available at: https://d1wqtxts1xzle7.cloudfront.net/34078649/G1055660-libre.pdf?1404165528=&response-content-disposition=inline%3B+filename%3DInternational_Journal_of_Engineering_Res.pdf&Expires=1746974639&Signature=V-Bw~GhzQcCi0BOTt~OOHw2RaVThPIOofzq60KanArrNdsoouDTRsmW6S5~sU9JgaVUCGD3gQnTPuAMvzeY40CWVXMJQ8T~goiFa~6zyccsBjW3jivLlqW1PunoQo7C~5gKYIlt9CcwQ~rLBBZbkfNnxA~QNAEHjX7zMSWb~1xC7l88oNALxC~QZXtRFlPw9kV9sPgWldCHfyN0HbyVgVco4tDOTCSSeX22WWtoxbl5H2J5-LaT2-x15YBocPyKs020f~5kEavezaUFawx~ImDgG4gREmz~dBeipltV~-mOymNJHaBYXPG2vCfmgDSEIDdVxy4rsExtVZkwTP11Bgg__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA (Accessed: 11 May 2025).

Stoss, K., Deere, J., Deere European, J., Sobotzik, J. and Kreis, E. (2013) *Tractor Power for Implement Operation-Mechanical, Hydraulic, and Electrical: An Overview Bin Shi*. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ea752bfd632a1b287cbfcce9ceacfa1e31c3196d (Accessed: 11 May 2025).

Sun, X., Lu, Z., Song, Y., Cheng, Z., Jiang, C., Qian, J. and Lu, Y. (2022) 'Development Status and Research Progress of a Tractor Electro-Hydraulic Hitch System', *Agriculture*, 12(10), p. 1547. Available at: https://www.mdpi.com/2077-0472/12/10/1547

Vähäoja, P. (2006) *OIL ANALYSIS IN MACHINE DIAGNOSTICS*. Available at: https://oulurepo.oulu.fi/bitstream/handle/10024/36056/isbn951-42-8076-8.pdf?sequence=1 (Accessed: 11 May 2025).

Woolley, S. (2025) Image of T7 270 Transmission and back end. Email to B. Davies 12 April

Zeng, R., Zhang, Y., Lin, Z.-R. and Sun, J.-K. (2016) 'Contamination analysis and monitoring methods of hydraulic fluid', in *Proceedings of the 3rd Annual International Conference on Mechanics and Mechanical Engineering (MME 2016)*, 21–23 October 2016, Shenzhen, China. Paris: Atlantis Press, pp. 377–381 Available at: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Contamination+Analysis+and+Monitoring+Methods+of+Hydraulic+Fluid.+In+3rd+Annual+International+Conference+on+Mechanics+and+Mechanical+Engineering+&btnG=

Appendices

Appendix 1: MP Filtri calibration certificate

Confirmation document supplied with the MP Filtri CML4 sampling devise.

MP Filtri UK Ltd
Keep House, Conference Way, Vale Park,
Evesham
England
WR11 1LB
Tel: +44 (0) 1386 258500
www.mpfiltri.co.uk

MPFILTRI Condition Monitoring Products Division

CERTIFICATE OF CALIBRATION

WE HEREBY CERTIFY THAT THE CONTAMINATION MONITORING PRODUCT DETAILED BELOW HAS BEEN FULLY CALIBRATED WITH ISO MEDIUM TEST DUST (MTD) BASED ON ISO 11171:2020 ON TEST EQUIPMENT CERTIFIED TO ISO 11943 BY I.F.T.S (Institut de la Filtration et des Techniques Séparatives).

We hereby confirm that the above mentioned measuring system was calibrated according to DIN ISO 9001, under the observation of a certified quality assurance system. The measuring installation used for calibration are regularly calibrated to national standards by I.F.T.S. Should no national standards exist, the measuring procedure corresponds with the technical regulations and norms valid at the time of the measurement

PRODUCT TYPE	CML4W0M001
SERIAL NUMBER	961010157
CERTIFICATE NUMBER	961010157 14 10 2024

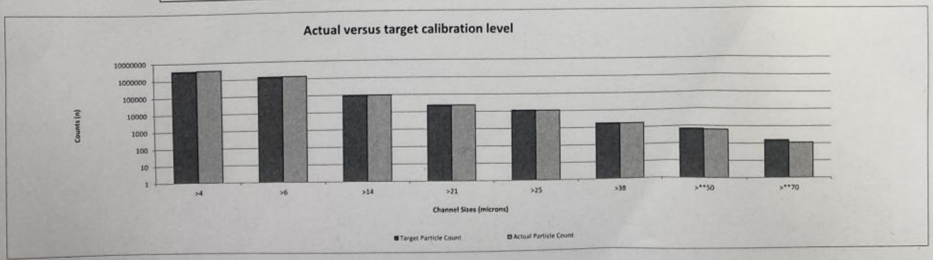
MEDIUM TEST DUST BATCH NUMBER	12798M
DATE OF CALIBRATION	14/10/24
CALIBRATION RIG NUMBER	00303

PARTICLE COUNT LIMITS AT 16mg/L CONCENTRATION
(Suspension of ISO MTD in MIL-H-5606)
No. particles reported per 100ml volume

Particle Size	Calibration Pulse Height	Target Particle Count	Actual Particle Count	Deviation	% Deviation (+/- 10%)
[microns (c)]	[mV]	[n]	[n]	[n]	[%]
>4	156	3480037	3592263	112226	3.22%
>6	334	1367463	1419841	52378	3.83%
>14	1932	97276	97808	532	0.55%
>21	4574	24205	24018	-187	-0.77%
>25	7510	11389	11137	-252	-2.21%
>38	18392	1787	1779	-8	-0.45%
>**50	26252	690	634	-	-
>**70	40184	160	113	-	-

***These particle sizes are not yet certified by NIST*

LS1 No Noise Threshold	LS1 Threshold Sensitivity	Sensitivity Threshold Ratio
[mV]	[mV]	[-]
75	81	[illegible]



CALIBRATION RESULT	PASS
RE-CALIBRATION DUE	1 YEAR FROM FIRST USE
CALIBRATED BY	Alex Buckley

PASS - VERIFIED

Position	Calibration Lab Technician

Newly purchased products are covered under warranty for 12 months from first use
Products being returned for re-calibration are verified for accuracy for a further 12 months. This does not extend the warranty.
Customers are responsible for managing the intervals between calibration's as defined within IS0 9001:2000

Batter declaration for the MP Filtri CML4

AA Portable Power Corp.
www.batteryspace.com, Email: Sales@batteryspace.com
825 S 19th Street, Richmond, CA 94804
Tel: 510-525-2328 Fax: 510-439-2808

DECLARATION OF CONFORMITY
UN38.3

We herewith confirm that each battery of this type is proved to meet the requirement of each applicable test in UN Manual of tests and Criteria, Part III, Section 38.3

Report Reference:	2014-002
Issue Date:	3/22/2014
Customer:	**AA Portable Power Corp.** 825 S 19th Street, Richmond, CA94804, USA Tel: 510-525-2328 www.BatterySpace.com E-mail: Sales@BatterySpace.com
Original Manufacturer:	**AA Portable Power Corp.** 825 S 19th Street, Richmond, CA94804, USA Tel: 510-525-2328 www.BatterySpace.com E-mail: Sales@BatterySpace.com
Product Description:	4S4P LFP-18650 LiFePO4 Battery Battery: 12.8V 6000mAh (76.8Wh, 2A rate) with PCB
Model Number:	CU-J744
Applied Standard:	UN ST/SG/AC.10/11/Rev.5, Amend.2,Section 38.3

Performed Tests:

T.1 Altitude Simulation	Request	Pass
T.2 Thermal Test	Request	Pass
T.3 Vibration	Request	Pass
T.4 Shock	Request	Pass
T.5 External Short Circuit	Request	Pass
T.6 Impact / Crush	N/A	N/A
T.7 Over Charge	Request	Pass
T.8 Forced Discharge	N/A	N/A

Test Laboratory: **AA Portable Power Corp.**
825 S 19th Street, Richmond, CA94804, USA
Tel: 510-525-2328
www.BatterySpace.com
E-mail: Rocky@BatterySpace.com

Rocky Xu Date: 5/16/2019
Rocky Xu, Lab Director

Appendix 2: ICP-MS laboratory process guide

ICP-MS Data Collection Process.

All HAU laboratories health and safety guidance and procedures, wearing correct PPE and lab coat should be followed.

Oil sample preparation and digestion.
The initial step requires weighing 0.5g of oil into a DigiTUBE using a KERN & Sohn GmbH electronic balance four place weigh scale.

1) Place an empty DigiTube onto the scale and set at zero.
2) Use a transfer pipette to transfer sample oil into DigiTUBE weighing 0.5g.
3) Remove and place on a clear plastic rack. For each sample it is necessary to duplicate the sample and clearly label e.g. 1A and 1B. For the first rack it is necessary to leave two blank tubes one for the reagent blank and another for the DigiPROBE. The following racks only require one blank after the first.
4) Repeat steps 1 to 3 for all collected samples.
5) Once all samples are weighed and prepped, it is necessary to add 1ml of conc. HCl, 6ml of conc. HNO_3 and 5ml of conc. H_2O_2 to all samples to start the digestion process, ensuring that the tubes do not touch the nozzle.
6) Place the DigiProbe into the first DigiTUBE in the reagent blank in the rack, it is important that the probe is immersed into the liquid but does not touching the bottom of the tube.
7) Place the sample rack of tubes into the slots of the DigiPREP Jr heating block, placing a plastic watch glass on top of each sample tube.
8) Turn on the DigiPREP and select Feeds method from the list, as selected run process shown in table and start the process.
9) Once the DigiPREP run has finished, remove from DigiPREP heating block and allow to cool in the fume cupboard.
10) Before the next oil sample batch can enter the DigiPREP heating block, it needs to cool down to below 30°.
11) Once the samples have cooled down, remove the plastic watch glasses from the top of the tubes and place them in the dedicated waste container. Dilute the cooled samples through adding ultra-pure water up to the 50ml mark on the DigiTUBE, closing the screw top lids and shaking before storing until prep for ICP-MS analysis.

Preparation for ICP-MS

ppm = mg/L

ppb = µl/kg

12) Construct a blank that contains 2% Nitric. Half fill a 1L volumetric flask with ultra-pure water and add 20ml of conc. Nitric acid, mixing thoroughly and inverting the flask 12 to 15 times.
13) Create 1000ppb Ga internal standard through half filling a clean 50ml test sample tube with ultra-pure water. Add 1ml of conc. Nitric acid followed by 50µl of 100ppm Gallium stock solution and fill to the marker with ultra-pure water, once sealed mix the solution by thoroughly shaking.
14) To create sample diluting acid, it is necessary to make up a blank at step 12, also adding 10.204ml of 1000ppb Ga internal standard through using an analytic balance to weigh. This provides a concentration of 10.204ppb of Ga. For a 1:20 dilution use 10.526g
15) To create calibration standard, first half fill 1liter volumetric flask with ultra-pure water, adding 20ml of conc. Nitric acid followed by 200µl of Al, As, Ba, B, Ca, Cr, Co, Cu, Fe, Li, Pb, Mo, Mg, Ma, Ni, Se, Si, Ti, Zn, 1000µl of Ca, P, K, Na and S 5000µl finalising the standard through filling ultra-pure water to the flask fill mark. Mix through inverting the flask 12-15 times.
16) Create working standards: Using the blank standard from step 12 to dilute and fill to 50ml mark of test sample tube.

    STD 1 25ppb: 1:2 dilution of STD2

    STD 2 50ppb: 1:2 dilution of STD 3

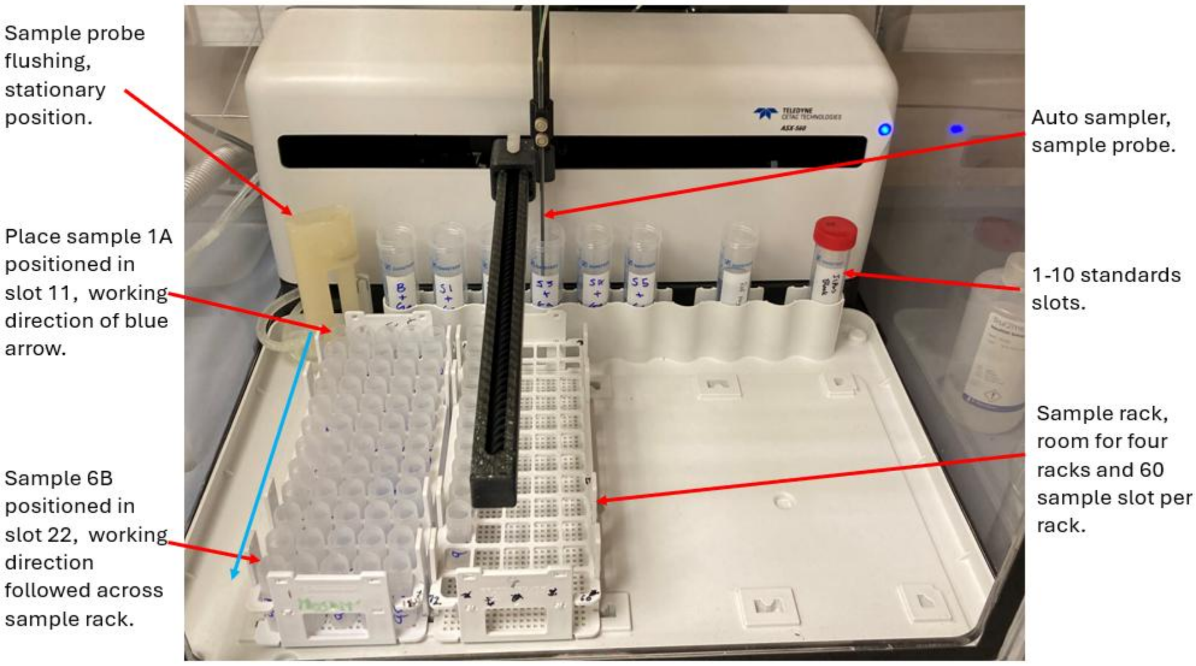
    STD 3 100ppb: 1:2 dilution of STD 4

    STD 4 200ppb: 1:2 dilution of STD 5, using the weigh scales weigh out 25.00g of standard 5 into a separate 50ml test tube ensuring that the empty tube zeroed before filling.

    STD 5: 400ppb of each element.

17) Using 2 place balance weigh 19.80g of each standard into a new 50ml sample tube and a pipette to ensure that sample tube is zeroed before adding the sample. Use a new pipette for each sample.
18) Add 200µl of Ga internal sample from step 12, giving a final concentration of the Ga internal standard of 10ppb in each standard. It is important to mix thoroughly through horizontal shaking.
19) The digested samples are diluted 1:50 and should be analysed in duplicates. Shake the sample DigiTube to mix the content before pipette 100µl of the sample into an empty auto sampler tube, changing the pipet tip for each sample to avoid cross contamination.

20) Add 4.90ml of sample diluting acid that contains the internal standards from step 15 into the auto sampler tube and screw on tube caps.
21) Repeat steps 19-20 for all samples.
22) Mix samples using vortex mixer and remove caps before placing in ICP-MS sampler. It is necessary to prepare a reference sample following the same procedure.
23) The samples must be laid out in the racks following format with sampling rack starting from position 11, as blank and reference sample are placed in position 1-10 on the auto sampler. After every 12 sample a standard and the reference sample are running as quality control checks to ensure that the instrumentation is working correctly.



Auto sampler and sample layout position.

<u>Running the ICP-MS</u>

24) Turn on the argon supply to the ICP-MS.
25) Ensure that all tubing is complete and not damaged, clamping in position.
26) Check the levels of blank solution in the auto sampler wash bottle. Empty the waste bottle if necessary.
27) Turn on the ICP-MS software to light the plasma a blue led should be lit. Allow the instrumentation to warm up for 10 minutes.
28) Ensure that the standards list of elements is uploaded and specified solution requirements are in line with samples.

Place the samples into the auto sampler following step 22. Place the Nexion set up solution in the auto sampler slot and run a standard performance check, if the sample successfully passes the instrumentation can be used to run the samples.

Appendix 3: MP Filtri data

Raw data provided by MP Filtri CML4

	Brand and oil type	Classification	µm/100ml	µm/100ml	µm/100ml	µm/100ml	µm/100ml	µm/100ml	µm/100ml	µm/100ml
			>4	>6	>14	>21	>25	>38	>50	>70
1	JD HYD and TRA	24/23/18	9621257	5641446	207609	110787	80547	53509	49207	47049
2	JD HYD and TRA	24/22/18	8261150	3921599	133848	122679	120001	113121	112329	110357
3	JD HYD and TRA	24/23/18	8636139	4456798	205046	178480	172898	167604	167604	165844
4	JD HYD and TRA	24/23/16	9334656	5323742	52056	44236	43245	41814	40983	39684
5	JD HYD and TRA	24/23/18	9199408	5133408	148719	146151	54036	52643	52229	52229
6	JD HYD and TRA	24/23/17	8849203	4250472	76434	65590	64790	64744	64744	64744
7	JD HYD and TRA	23/21/16	6076722	1763869	43264	39796	39251	36504	35363	31310
8	JD HYD and TRA	24/23/17	8910138	4607085	81876	74777	73187	72156	71811	67271
9	JD HYD and TRA	24/23/16	9710926	5761965	62151	54749	54285	52631	52569	50692
10	JD HYD and TRA	23/22/18	6680311	2382409	130995	122186	120034	114211	112436	110972
11	Fendt TRA	23/21/18	4611019	1563635	215257	182906	180167	176271	172869	172342
12	Fendt TRA	23/22/20	5801989	2477045	960157	91796	86251	86032	85725	82310
13	Fendt TRA	23/22/20	6679331	3139745	555081	51302	43652	39713	39437	39004
14	Fendt TRA	23/21/20	5420631	1810185	500516	47268	42825	40398	38671	38207
15	Fendt TRA	23/21/19	4765700	1250152	361524	360024	347495	343567	340382	340382
16	Fendt TRA	23/22/20	6745154	3257522	709098	684592	684592	684592	684592	684592
17	Fendt TRA	24/23/20	8376793	4824992	526252	476548	472648	270534	161896	161896
18	Fendt TRA	23/21/20	4413154	1230127	509160	438224	438224	224566	214546	214546
19	Fendt TRA	22/21/20	3810056	1197137	768282	723378	68446	60732	60072	60072
20	Fendt TRA	23/21/19	4593146	1033088	203484	140635	87459	63924	59862	58471
21	Fendt HYD1	24/23/20	9153615	6491184	782741	342137	251614	201840	201840	201840
22	Fendt HYD1	24/23/21	8106490	6160946	767810	65839	44053	30800	30800	30800
23	Fendt HYD1	24/23/21	9742032	6382347	963693	92317	87362	86472	86087	83422
24	Fendt HYD1	24/23/20	9867583	6548271	746248	708627	15816	15376	14663	14663
25	Fendt HYD1	24/23/21	8271248	4773682	915483	836224	435521	21361	21055	21055
26	Fendt HYD2	23/22/21	7034378	3867429	834581	786288	786288	783216	780338	780338
27	Fendt HYD2	24/23/20	8637246	4978416	798483	764836	394481	390264	206628	206628
28	Fendt HYD2	24/22/20	8469242	3614733	773941	748725	386491	382532	382532	382532
29	Fendt HYD2	23/21/20	6682561	1986793	786183	752413	372249	370167	181459	181272
30	Fendt HYD2	24/23/21	9674183	5862447	934356	913153	85631	85631	82847	82073
31	New JD HYD and TRA	22/19/14	2744371	378389	13905	10994	10439	9471	9081	8579
32	New Fendt TRA	23/20/15	4226496	817085	31993	26603	26603	26603	26603	26603
33	New Fendt HYD1	23/20/14	4749794	839173	12571	6609	5678	5084	5071	5071
34	New Fendt HYD2	20/18/16	838461	245511	39922	19725	14562	11753	11753	11753

Data recorded from CML4 and filtered through dividing by 100.

Brand and oil type	Classification	Particle count		
		>4	>6	>14
JD HYD and TRA	24/23/18	96213	56414	2076
JD HYD and TRA	24/22/18	82612	39216	1338
JD HYD and TRA	24/23/18	86361	44568	2050
JD HYD and TRA	24/23/16	93347	53237	521
JD HYD and TRA	24/23/18	91994	51334	1487
JD HYD and TRA	24/23/17	88492	42505	764
JD HYD and TRA	23/21/16	60767	17639	433
JD HYD and TRA	24/23/17	89101	46071	819
JD HYD and TRA	24/23/16	97109	57620	622
JD HYD and TRA	23/22/18	66803	23824	1310
Fendt TRA	23/21/18	46110	15636	2153
Fendt TRA	23/22/20	58020	24770	9602
Fendt TRA	23/22/20	66793	31397	5551
Fendt TRA	23/21/20	54206	18102	5005
Fendt TRA	23/21/19	47657	12502	3615
Fendt TRA	23/22/20	67452	32575	7091
Fendt TRA	24/23/20	83768	48250	5263
Fendt TRA	23/21/20	44132	12301	5092
Fendt TRA	22/21/20	38101	11971	7683
Fendt TRA	23/21/19	45931	10331	2035
Fendt HYD1	24/23/20	91536	64912	7827
Fendt HYD1	24/23/21	81065	61609	7678
Fendt HYD1	24/23/21	97420	63823	9637
Fendt HYD1	24/23/20	98676	65483	7462
Fendt HYD1	24/23/21	82712	47737	9155
Fendt HYD2	23/22/21	70344	38674	8346
Fendt HYD2	24/23/20	86372	49784	7985
Fendt HYD2	24/22/20	84692	36147	7739
Fendt HYD2	23/21/20	66826	19868	7862
Fendt HYD2	24/23/21	96742	58624	9344
New JD HYD and	22/19/14	27444	3784	139
New Fendt TRA	23/20/15	42265	8171	320
New Fendt HYD1	23/20/14	47498	8392	126
New Fendt HYD2	20/18/16	8385	2455	399

Genstat data processing

Analysis of variance <4 to <70 (Repeated measurement ANOVA)

Analysis of variance

Variate: %gt4,%gt6,%gt14,%gt21,%gt25,%gt38,%gt50,%gt70

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Subject stratum					
Brand	3	2.845E+13	9.483E+12	11.24	<.001
Residual	26	2.194E+13	8.440E+11	2.44	
Subject.Time stratum					
d.f. correction factor 0.1656					
Time	7	1.540E+15	2.200E+14	636.42	<.001
Time.Brand	21	9.531E+13	4.539E+12	13.13	<.001
Residual	182	6.293E+13	3.458E+11		
Total	239	1.749E+15			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

Subject 7	-663175.	approx. s.e. 302376.
Subject 17	738219.	approx. s.e. 302376.
Subject 7 Time %gt4	-1788094.	approx. s.e. 512054.
Subject 7 Time %gt6	-1897236.	approx. s.e. 512054.
Subject 10 Time %gt6	-1492130.	approx. s.e. 512054.
Subject 17 Time %gt4	2116876.	approx. s.e. 512054.
Subject 17 Time %gt6	1908410.	approx. s.e. 512054.
Subject 29 Time %gt6	-1584208.	approx. s.e. 512054.
Subject 30 Time %gt6	1490543.	approx. s.e. 512054.

Tables of means

Variate: %gt4,%gt6,%gt14,%gt21,%gt25,%gt38,%gt50,%gt70

Grand mean 1613299.

Time	%gt4	%gt6	%gt14	%gt21	%gt25	%gt38	%gt50
	7537849.	3856422.	491811.	338889.	204451.	170898.	153519.

Time	%gt70
	152553.

Brand	Fendt HYD 1	Fendt HYD 2	Fendt TRA
	2090374.	1905100.	1170726.
rep.	40	40	80

Brand	New JD HYD and TRA
	1671435.
rep.	80

Time	Brand	Fendt HYD 1	Fendt HYD 2	Fendt TRA
%gt4		9028194.	8099522.	5521697.
	rep.	5	5	10
%gt6		6071286.	4061964.	2178363.
	rep.	5	5	10
%gt14		835195.	825509.	530881.
	rep.	5	5	10
%gt21		409029.	793083.	319667.
	rep.	5	5	10
%gt25		166873.	405028.	245176.
	rep.	5	5	10
%gt38		71170.	402362.	199033.
	rep.	5	5	10
%gt50		70889.	326761.	185805.
	rep.	5	5	10
%gt70		70356.	326569.	185182.
	rep.	5	5	10

Time	Brand	New JD HYD and TRA
%gt4		8527991.
	rep.	10
%gt6		4324279.
	rep.	10
%gt14		114200.
	rep.	10
%gt21		95943.
	rep.	10
%gt25		82227.
	rep.	10
%gt38		76894.
	rep.	10
%gt50		75927.
	rep.	10
%gt70		74015.
	rep.	10

Standard errors of means

Table	Time	Brand	Time Brand	
rep.	30	unequal	unequal	
e.s.e.	107355.7	145256.9	285669.5	min.rep
d.f.	30.13	26	48.04	
e.s.e.		102712.2	201998.9	max.rep
d.f.		26	48.04	
Except when comparing means with the same level(s) of				
Brand			262966.6	min.rep
d.f.			30.13	
			185945.4	max.rep
d.f.			30.13	

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %gt4,%gt6,%gt14,%gt21,%gt25,%gt38,%gt50,%gt70

Stratum	d.f.	s.e.	cv%
Subject	26	324804.4	20.1
Subject.Time	182	588011.1	36.4

Tukey's 95% confidence intervals

Brand

	Mean	
Fendt TRA	1170726	a
New JD HYD and TRA	1671435	b
Fendt HYD 2	1905100	b
Fendt HYD 1	2090374	b

Analysis of variance <4 to <14 (Repeated measurement ANOVA)

Analysis of variance

Variate: %gt4,%gt6,%gt14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Subject stratum					
Brand	3	7.776E+13	2.592E+13	12.60	<.001
Residual	26	5.348E+13	2.057E+12	3.91	
Subject.Time stratum					
d.f. correction factor 0.6000					
Time	2	7.452E+14	3.726E+14	707.98	<.001
Time.Brand	6	4.305E+13	7.175E+12	13.63	<.001
Residual	52	2.737E+13	5.263E+11		
Total	89	9.469E+14			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

Subject 7	-1694205.	approx. s.e. 770840.
Subject 17	1832365.	approx. s.e. 770840.
Subject 7 Time %gt14	1623269.	approx. s.e. 551431.
Subject 17 Time %gt14	-1836994.	approx. s.e. 551431.

Tables of means

Variate: %gt4,%gt6,%gt14

Grand mean 3962027.

Time	%gt4	%gt6	%gt14
	7537849.	3856422.	491811.

Brand	Fendt HYD 1	Fendt HYD 2	Fendt TRA
	5311558.	4328998.	2743647.
rep.	15	15	30

Brand	New JD HYD and TRA
	4322157.
rep.	30

Time	Brand	Fendt HYD 1	Fendt HYD 2	Fendt TRA
%gt4		9028194.	8099522.	5521697.
	rep.	5	5	10
%gt6		6071286.	4061964.	2178363.
	rep.	5	5	10
%gt14		835195.	825509.	530881.
	rep.	5	5	10

Time	Brand	New JD HYD and TRA
%gt4		8527991.
	rep.	10
%gt6		4324279.
	rep.	10
%gt14		114200.
	rep.	10

Standard errors of means

Table	Time	Brand	Time Brand	
rep.	30	unequal	unequal	
e.s.e.	132449.5	370299.8	455294.9	min.rep
d.f.	31.20	26	48.77	
e.s.e.		261841.5	321942.1	max.rep
d.f.		26	48.77	
Except when comparing means with the same level(s) of				
Brand			324433.7	min.rep
d.f.			31.20	
			229409.3	max.rep
d.f.			31.20	

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %gt4,%gt6,%gt14

Stratum	d.f.	s.e.	cv%
Subject	26	828015.5	20.9
Subject.Time	52	725455.9	18.3

Tukey's 95% confidence intervals

Brand

	Mean	
Fendt TRA	2743647	a
JD Combined	4322157	b
Fendt HYD 2	4328998	b
Fendt HYD 1	5311558	b

Statisty data

Aluminium (Al)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Al (mg/kg)	JD HYD and TRA	20	12.27	1.54	10.04	15.46	5.43	12.27 ± 1.54
	Fendt TRA	20	10.86	1.2	8.33	13.38	5.04	10.86 ± 1.2
	Fendt HYD1	10	14.39	2.47	11.31	18.21	6.9	14.39 ± 2.47
	Fendt HYD2	10	11.09	0.88	10.02	12.64	2.61	11.09 ± 0.88
	New JD HYD and TRA	2	8.98	0.49	8.63	9.33	0.7	8.98 ± 0.49
	New Fendt TRA	2	8.51	0.44	8.19	8.82	0.63	8.51 ± 0.44
	New Fendt HYD1	2	9.86	1.49	8.81	10.91	2.11	9.86 ± 1.49
	New Fendt HYD2	2	11.76	0.77	11.21	12.31	1.09	11.76 ± 0.77

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	138.74	7	19.82	8.66	<.001
Residual	137.36	60	2.29		
Total	276.09	67			

Copper (Cu)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Cu (mg/kg)	JD HYD and TRA	20	19.7	3.73	13.44	25.3	11.87	19.7 ± 3.73
	Fendt TRA	20	53.58	44.91	6.76	146.08	139.31	53.58 ± 44.91
	Fendt HYD1	10	9.6	5.39	7.04	24.35	17.31	9.6 ± 5.39
	Fendt HYD2	10	10.59	2.28	8.23	15.52	7.29	10.59 ± 2.28
	New JD HYD and TRA	2	0.03	0.05	0	0.07	0.07	0.03 ± 0.05
	New Fendt TRA	2	0	0	0	0	0	0 ± 0
	New Fendt HYD1	2	0.1	0.14	0	0.2	0.2	0.1 ± 0.14
	New Fendt HYD2	2	0.16	0.05	0.12	0.19	0.06	0.16 ± 0.05

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	26295.86	7	3756.55	5.8	<.001
Residual	38890.79	60	648.18		
Total	65186.65	67			

Iron (Fe)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Fe (mg/kg)	JD HYD and TRA	20	38.61	5.45	29.36	50.19	20.82	38.61 ± 5.45
	Fendt TRA	20	41.14	30.49	11.28	99.32	88.04	41.14 ± 30.49
	Fendt HYD1	10	60.01	21.38	40.48	100.13	59.65	60.01 ± 21.38
	Fendt HYD2	10	26.98	6.43	19.45	38.33	18.88	26.98 ± 6.43
	New JD HYD and TRA	2	1.13	0.25	0.96	1.31	0.35	1.13 ± 0.25
	New Fendt TRA	2	1.05	0.63	0.6	1.5	0.9	1.05 ± 0.63
	New Fendt HYD1	2	3.33	0.47	2.99	3.66	0.67	3.33 ± 0.47
	New Fendt HYD2	2	2.78	1.57	1.67	3.89	2.22	2.78 ± 1.57

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	16442.48	7	2348.93	6.2	<.001
Residual	22714.31	60	378.57		
Total	39156.8	67			

Tin (Sn)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Sn (mg/kg)	JD HYD and TRA	20	24881.7	6711.16	13391.19	37346.56	23955.37	24881.7 ± 6711.16
	Fendt TRA	20	8858.09	7621.08	1641.88	26636.78	24994.9	8858.09 ± 7621.08
	Fendt HYD1	10	4376.8	3112.56	2025.58	10517.9	8492.33	4376.8 ± 3112.56
	Fendt HYD2	10	11635.63	5565.85	8085.96	22716.27	14630.31	11635.63 ± 5565.85
	New JD HYD and TRA	2	0	0	0	0	0	0 ± 0
	New Fendt TRA	2	0	0	0	0	0	0 ± 0
	New Fendt HYD1	2	0	0	0	0	0	0 ± 0
	New Fendt HYD2	2	0	0	0	0	0	0 ± 0

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	5245391244.75	7	749341606.39	19.34	<.001
Residual	2325290607.63	60	38754843.46		
Total	7570681852.37	67			

Calcium (Ca)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Ca (mg/kg)	JD HYD and TRA	20	2838.14	178.72	2399.43	3107.81	708.38	2838.14 ± 178.72
	Fendt TRA	20	3318.91	407.5	2630.82	4274.37	1643.55	3318.91 ± 407.5
	Fendt HYD1	10	2542.32	164.86	2243.37	2774.19	530.82	2542.32 ± 164.86
	Fendt HYD2	10	2326.04	168.43	2017.13	2563.15	546.02	2326.04 ± 168.43
	New JD HYD and TRA	2	3536.76	45.7	3504.45	3569.08	64.63	3536.76 ± 45.7
	New Fendt TRA	2	3162.77	43.6	3131.94	3193.6	61.66	3162.77 ± 43.6
	New Fendt HYD1	2	2974.45	56.95	2934.18	3014.72	80.54	2974.45 ± 56.95
	New Fendt HYD2	2	2420.44	146.68	2316.72	2524.16	207.44	2420.44 ± 146.68

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	9559272.65	7	1365610.38	19.1	<.001
Residual	4290665.38	60	71511.09		
Total	13849938.03	67			

Zinc (Zn)

		Frequency	Mean	Std. Deviation	Minimum	Maximum	Range	Mean ± Std.
Zn (mg/kg)	JD HYD and TRA	20	1174.78	63.01	1012.83	1311.04	298.21	1174.78 ± 63.01
	Fendt TRA	20	1311.19	167.42	1071.24	1709.56	638.32	1311.19 ± 167.42
	Fendt HYD1	10	1038.26	63.11	920.53	1126.41	205.88	1038.26 ± 63.11
	Fendt HYD2	10	1055.54	59.26	953.26	1128.91	175.64	1055.54 ± 59.26
	New JD HYD and TRA	2	1386.45	2.24	1384.87	1388.03	3.16	1386.45 ± 2.24
	New Fendt TRA	2	1201.64	32.14	1178.91	1224.36	45.46	1201.64 ± 32.14
	New Fendt HYD1	2	1186.81	9.35	1180.19	1193.42	13.23	1186.81 ± 9.35
	New Fendt HYD2	2	1053.73	61.46	1010.28	1097.19	86.91	1053.73 ± 61.46

	Sum of Squares	df	Mean Squares	F	p
Brand & Oil type	818626.28	7	116946.61	10.31	<.001
Residual	680351.76	60	11339.2		
Total	1498978.04	67			

Appendix 4: ISO 4406 code classification chart.

ISO 4406 classification chart

ISO 4406 - Allocation of Scale Numbers

Class	Number of particles per ml	
	Over	Up to
28	1 300 000	2 500 000
27	640 000	1 300 000
26	320 000	640 000
25	160 000	320 000
24	80 000	160 000
23	40 000	80 000
22	20 000	40 000
21	10 000	20 000
20	5 000	10 000
19	2 500	5 000
18	1 300	2 500
17	640	1 300
16	320	640
15	160	320
14	80	160
13	40	80
12	20	40
11	10	20
10	5	10
9	2.5	5
8	1.3	2.5
7	0.64	1.3
6	0.32	0.64
5	0.16	0.32
4	0.08	0.16
3	0.04	0.08
2	0.02	0.04
1	0.01	0.02
0	0	0.01

> 4 $\mu m_{(c)}$ = 350 particles
> 6 $\mu m_{(c)}$ = 100 particles
> 14 $\mu m_{(c)}$ = 25 particles
16 / 14 / 12

Source: Adapted from MP Filtri, 2022)

Appendix 5: ICP-MS data from analysis

Original oil sample weight used for ICP-MS analysis when weighing out using four place electronic balance weigh scales.

Sample Id	Oil sample weight (g)
1A	0.4638
1B	0.4687
2A	0.4907
2B	0.4662
3A	0.4891
3B	0.485
4A	0.4764
4B	0.4807
5A	0.4706
5B	0.4769
6A	0.4921
6B	0.4813
7A	0.4825
7B	0.4916
8A	0.4917
8B	0.497
9A	0.4925
9B	0.4925
10A	0.485
10B	0.4851
11A	0.494
11B	0.494
12A	0.485
12B	0.4853
13A	0.4958
13B	0.485
14A	0.483
14B	0.4906
15A	0.4909
15B	0.4907
16A	0.4967
16B	0.4906
17A	0.4959
17B	0.4953
18A	0.4811
18B	0.4999

18B	0.4999
19A	0.4988
19B	0.492
20A	0.4987
20B	0.491
21A	0.4942
21B	0.4925
22A	0.4958
22B	0.4995
23A	0.4907
23B	0.4999
24A	0.4999
24B	0.492
25A	0.4934
25B	0.4992
26A	0.4981
26B	0.4967
27A	0.4961
27B	0.497
28A	0.4922
28B	0.4993
29A	0.4989
29B	0.4962
30A	0.4918
30B	0.4938
31A	0.4966
31B	0.499
32A	0.4999
32B	0.4955
33A	0.4967
33B	0.498
34A	0.4999
34B	0.493

ICP-MS Filtered data.

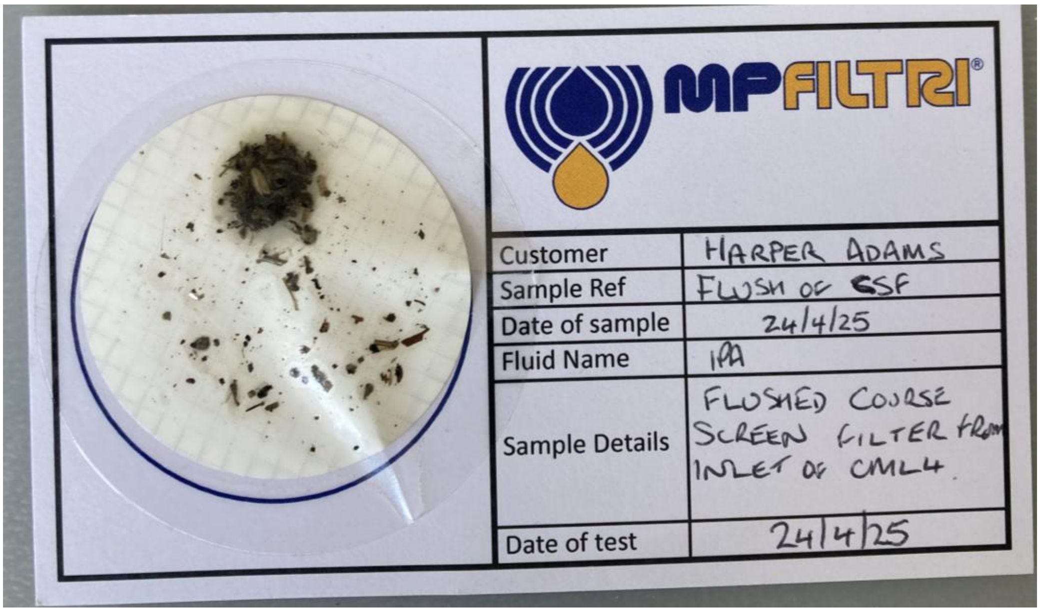
Row	Brand & Oil type	Sample	Al (mg/kg)	As (mg/kg)	B (mg/kg)	Ba (mg/kg)	Ca (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Mo (mg/kg)	Na (mg/kg)	Ni (mg/kg)	P (mg/kg)	Pb (mg/kg)	S (mg/kg)	Se (mg/kg)	Si (mg/kg)	Sn (mg/kg)	Ti (mg/kg)	Zn (mg/kg)
1	JD HYD and TRA	1A	13.50626	0.0892903	46.55938	0.846638	2888.105	0.068713	0.5177	22.22986335	39.39918	77.97123	27.07018	1.819679	4.716919	113.1722	0.412032	827.8235	3.546542	2168.481	0	0	31253.53	2.17116	1228.640993
2	JD HYD and TRA	1B	12.07994	0.0634596	47.43162	0.768639	2882.499	0.02008	0.544233	23.22198464	50.18738	0.875705	13.61918	1.548732	3.169584	0	0.349616	842.1021	3.595794	4234.686	1.18111	0	33232.83	2.014338	1249.676022
3	JD HYD and TRA	2A	12.90191	0.0497809	52.38373	1.027731	3107.814	0.028851	0.39734	22.4313171	37.11906	76.26742	17.49777	0.976665	3.167268	95.16051	0.321924	890.7851	4.036606	5234.528	2.913361	11.69988	16689	2.351165	1311.043175
4	JD HYD and TRA	2B	15.13597	0.0118422	51.67034	0.876893	2713.857	0.047284	0.361319	19.7017724	37.01242	59.37201	15.94397	0.79656	2.848609	63.42129	0.202849	837.514	3.379196	5222.063	0.816148	0	22145.5	1.860501	1144.675384
5	JD HYD and TRA	3A	11.7488	0.0275581	52.15294	0.848594	2621.781	0.019305	0.379162	22.01990595	38.24939	17.77547	13.9909	0.854759	2.757993	8.011207	0.147867	810.1051	3.669447	5464.956	0	1.96937	29798.27	2.069344	1164.3439
6	JD HYD and TRA	3B	11.39381	0.0537626	48.24478	0.700024	2613.792	0.025535	0.454806	21.75264305	38.758	0	13.81968	0.871992	2.657559	2.501253	0.224843	806.2394	3.493217	3954.43	0.538201	0	28319.53	1.891132	1147.223484
7	JD HYD and TRA	4A	12.53755	0.0469406	43.04441	0.74028	2807.126	0.027566	0.357934	16.32491797	43.26778	0	14.49532	0.745909	2.941223	0.969157	0.205942	837.8036	2.776637	4343.481	-0.40391	0	21087.89	2.057547	1134.267596
8	JD HYD and TRA	4B	10.64628	0.0336132	43.27448	0.658919	2866.301	0.02485	0.340592	17.74683791	40.16508	0	15.14662	0.720623	2.834148	2.809033	0.191425	842.2807	2.998486	4353.518	0	0	22280.18	2.130269	1182.22416
9	JD HYD and TRA	5A	11.65465	0.0332427	43.50131	0.734632	3009.078	0.014672	0.345829	15.72504288	40.39825	0	16.19913	0.819426	2.976151	32.14608	0.196247	848.5509	2.843447	4678	0	0	20939.37	2.083716	1256.928005
10	JD HYD and TRA	5B	12.18641	0.0518535	41.69721	0.668474	2969.546	0.003388	0.361996	13.84870668	40.29474	0	15.18445	0.988201	2.931916	105.6111	0.211663	862.9598	2.437308	4218.752	0.329171	0	21218.04	2.129641	1107.825069
11	JD HYD and TRA	6A	10.03568	0	47.44809	0.80464	2785.595	0.007879	0.343521	24.45085997	35.4127	0	15.35121	0.818183	2.704709	1.867293	0.184016	791.1826	3.830534	3957.468	0.23066	0	22749.51	2.042476	1193.1316
12	JD HYD and TRA	6B	12.72893	0	49.31088	3.508937	2612.863	0.022799	0.548898	22.89505562	43.277	0	13.97222	0.918428	2.800261	11.99483	0.381295	813.929	3.457087	3706.426	0.257518	0	26840.74	2.088278	1156.170291
13	JD HYD and TRA	7A	10.47817	0.0317885	49.90895	0.623661	2399.431	0.034754	2.070375	16.2455181	29.36448	17.20944	12.40772	0.705108	2.770383	21.14256	0.16079	791.0783	2.657302	2250.51	0	67.3981	21652.12	1.809056	1012.83178
14	JD HYD and TRA	7B	11.33591	0.0197081	54.07739	0.679755	2856.375	0.031176	0.839311	18.65178366	33.79871	0	15.05154	0.778862	2.808784	19.16028	0.444054	826.6938	2.933528	3056.936	0	4.718509	22825.57	1.879882	1120.704047
15	JD HYD and TRA	8A	10.26312	0.038799	49.28504	0.812557	2875.407	0.033082	0.344447	20.46275472	36.02304	0	16.017	0.812206	3.087681	3.656982	0.168045	855.311	3.281325	3330.052	0.215408	0	28614.31	1.971744	1163.607291
16	JD HYD and TRA	8B	11.2386	0.0213101	48.8856	0.88774	3058.56	0.017208	0.334471	20.56103595	36.07997	0	17.4503	0.886191	3.105287	4.166309	0.17367	863.7256	3.358495	3651.398	0	0	27072.35	2.149402	1180.783773
17	JD HYD and TRA	9A	14.5285	0.0152334	51.15966	0.74174	2782.497	0.009201	0.349904	23.13755157	45.18445	0	14.38532	0.959732	2.789054	0.260334	0.19006	796.5166	3.597011	3409.934	0	0	36389.74	1.823276	1141.38434
18	JD HYD and TRA	9B	15.46214	0.0539995	52.07297	0.863114	3075.216	0.025425	0.379348	25.30109287	46.89889	0	16.21372	0.989531	2.822669	14.34574	0.266134	807.4269	4.060694	3659.077	0	0	37346.56	2.125024	1214.938267
19	JD HYD and TRA	10A	12.35117	0.0274839	61.11655	0.79744	2931.917	0.014691	0.453541	13.43532002	31.26836	0	22.79626	0.824333	6.327077	11.1378	0.236857	872.554	2.778425	4646.384	0	0	13391.19	2.050398	1204.519264
20	JD HYD and TRA	10B	13.27324	0.0302311	59.15886	0.995728	2904.954	0.005199	0.307648	13.92987465	29.97699	119.7579	25.39446	0.710911	6.345479	214.1116	0.214693	891.2538	2.658397	4327.086	0	0	13787.78	2.184078	1180.738648
21	Fendt TRA	11A	12.32156	0	62.02671	1.218193	4274.374	0.015517	0.173855	7.01102878	11.27742	0	16.61046	0.746478	1.720332	4.468004	0.061297	1149.43	2.013495	5369.196	0.360861	18.20266	1678.385	2.924842	1709.557074
22	Fendt TRA	11B	12.02758	0.0049207	58.33154	1.221726	3759.653	0.007319	0.173836	6.76406336	11.78504	5.287884	15.90422	0.732668	1.653494	41.47576	0.100237	1014.782	1.811159	5146.343	0	21.35054	1641.878	2.867412	1570.384216
23	Fendt TRA	12A	10.37606	0.0270378	10.30935	11.28335	3179.808	0.256242	3.295445	103.3865518	29.85063	0	22.77634	0.597287	8.767348	27.4644	5.623893	1178.97	3.689654	5386.219	0.039023	0	3149.337	2.003495	1218.216123
24	Fendt TRA	12B	10.33389	0.0143122	10.30826	12.2962	3408.001	0.234039	0.981199	112.5664707	36.4727	0	24.26038	0.641517	4.107378	5.265663	1.380723	1252.146	3.871914	6098.217	0	0.570508	3804.815	2.142506	1281.850196
25	Fendt TRA	13A	10.44294	0.0525533	16.28593	3.549643	2630.824	0.229212	1.235593	84.25972333	97.92453	30.46882	15.16011	1.654624	4.66578	7.20607	1.219813	1234.451	7.054982	8607.013	0.627459	80.24284	23543.54	1.947205	1078.409934
26	Fendt TRA	13B	11.42439	0.0207445	17.1273	3.178566	2795.389	0.182581	0.929527	84.18352433	97.24423	0	13.44315	1.485826	4.012116	11.42094	0.639708	1180.55	7.171867	8582.398	0	22.30822	26636.78	1.948934	1071.235073
27	Fendt TRA	14A	11.71055	0.0198042	36.2659	0.704428	3276.112	0.159045	0.75859	146.0753689	98.30718	0	25.63069	1.640092	2.58429	0	0.511394	1001.311	6.099206	4716.672	0	0	17927.71	2.290444	1342.47579
28	Fendt TRA	14B	13.37733	0	37.41071	0.520191	3224.753	0.182874	0.708787	145.031838	99.32074	0	26.69683	1.683729	2.447234	0	0.469033	1007.104	6.015317	5205.381	0.845733	17.30956	17335.96	2.554568	1359.491511
29	Fendt TRA	15A	10.48002	0.0126861	12.69248	13.93098	3358.343	0.278098	0.447843	26.90861383	43.09322	0	38.90317	0.993979	3.83558	2.79669	0.265474	1299.858	4.704832	4925.728	0	0	4215.988	2.217883	1268.596936
30	Fendt TRA	15B	10.8153	0.0163321	12.75037	14.39734	3547.735	0.246752	0.436522	28.97606651	42.10935	0	42.17352	1.005633	3.982117	3.068185	0.250288	1421.855	4.8709	5483.332	0	0	4476.438	2.276707	1377.084304
31	Fendt TRA	16A	11.2679	0.0090281	5.509519	0.797172	2870.484	0.22398	0.308382	68.71620359	32.93303	733.1963	61.26308	0.833512	2.145873	1681.131	0.154464	1404.892	8.001484	4107.308	0	0	15360.07	2.106165	1128.099902
32	Fendt TRA	16B	9.186474	0.0180738	4.456728	0.215363	2851.652	0.198098	0.292524	65.90645792	30.7736	0	13.02605	0.681062	2.038557	0.017391	0.116423	1164.676	7.659664	3815.683	0	0	15625.77	2.173412	1105.435582
33	Fendt TRA	17A	8.332661	0.0186065	3.45579	0.418141	2970.387	0.227305	0.284835	19.38361964	21.67963	0	11.88981	0.508798	1.508282	0.501465	0.112337	1222.654	3.21831	4225.686	0.531855	0	2984.747	1.991965	1187.469519
34	Fendt TRA	17B	9.674971	0	4.290076	0.5146	2911.946	0.228292	0.408803	19.13058619	25.89698	16.80905	12.59471	0.576596	1.442872	68.23743	0.143515	1219.436	3.156832	4372.151	0	0	3316.004	2.484707	1178.59438
35	Fendt TRA	18A	9.781016	0	33.63569	0.624843	3348.45	0.097136	0.31286	35.38242014	28.47825	0	9.679185	0.721166	1.15483	4.990312	0.23255	1010.155	3.087849	4983.318	0	0	6458.014	2.399059	1289.521647
36	Fendt TRA	18B	10.04346	0	35.48703	0.802124	3669.031	0.085549	0.296893	37.49022433	29.41259	33.69385	13.11155	0.867728	1.204221	78.35814	0.225043	1053.658	3.337019	4832.512	0.254173	0	7970.008	2.312831	1395.532106
37	Fendt TRA	19A	11.3974	0	47.97922	0.17139	3521.886	0.029331	0.165565	15.29835057	15.45224	0	10.44898	0.662959	0.965119	5.442205	0.079274	912.9144	1.236178	3130.464	0.228497	0	4117.663	2.490089	1411.39133
38	Fendt TRA	19B	12.43422	0	51.50954	0.291749	3848.918	0.022817	0.186974	16.55298157	17.19759	0	11.21877	0.6484	0.995264	8.14433	0.073938	1002.008	1.33108	4059.49	0	0	4585.261	2.687168	1519.479933
39	Fendt TRA	20A	10.49327	0	41.58874	0.436714	3382.602	0.025348	0.271814	24.25971665	25.94549	0	11.60394	0.745722	1.147596	7.812055	0.121539	912.6161	2.098319	4077.655	0	0	6404.248	2.153523	1353.180792
40	Fendt TRA	20B	11.25866	0	43.60013	0.512075	3547.841	0.028043	0.314174	24.23210858	27.62135	0	10.4815	0.773252	1.148279	25.66603	0.160095	962.2676	2.1063	4848.346	0	0	5929.242	2.405073	1377.77103
41	Fendt HYD1	21A	14.12521	0.0206021	32.0418	2.744236	2417.387	0.062915	0.41795	7.531108691	42.25188	0	16.58538	0.75837	3.762061	18.30447	0.179259	783.5128	2.45092	3868.702	0.039318	0	3837.994	1.924718	996.0573042
42	Fendt HYD1	21B	11.79245	0	32.72528	2.614873	2484.085	0.057193	0.43112	7.935299744	45.83501	0	15.64475	0.78717	3.906822	21.46851	0.249179	818.6087	2.523549	3938.415	0.726229	0	3132.433	1.700399	1037.621264
43	Fendt HYD1	22A	13.19258	0.0203913	28.42184	5.411581	2696.517	0.081611	0.346202	7.042031054	40.4785	8.877373	17.03795	0.639477	4.081651	43.89838	0.20721	868.1233	2.780645	3901.647	0	0	2132.524	1.752875	1090.038899
44	Fendt HYD1	22B	11.31238	0	28.91833	5.580886	2774.194	0.086397	0.478235	7.129553739	41.80353	0	16.78615	0.696262	4.33617	9.877878	0.202239	905.0674	2.873418	4173.265	0	0	2730.704	1.943812	1126.409284
45	Fendt HYD1	23A	12.93547	0.0067409	28.02222	4.063825	2727.239	0.061207	0.412805	7.513409119	53.0397	55.11994	19.57814	0.844962	4.251416	116.1327	0.306036	855.5943	2.548483	4406.888	0.101546	0	2025.575	1.849385	1063.736442
46	Fendt HYD1	23B	16.57166	0.0142299	30.00656	4.059778	2635.263	0.067487	0.361982	7.464542191	59.63307	0	21.21372	1.031772	4.288112	10.5035	0.241177	890.0119	2.507855	4414.234	0.083719	0	3309.121	1.817326	1100.113179
47	Fendt HYD1	24A	12.31279	0.011606	29.46309	4.411189	2425.478	0.072594	0.429071	7.243659708	61.92625	0	16.15085	0.878394	4.015834	18.46285	0.297936	843.6975	2.383609	4071.948	0.777041	0	2994.471	1.773303	998.7294927
48	Fendt HYD1	24B	17.2034	0	31.09644	4.575023	2517.01	0.090723	0.449131	7.730575595	60.03857	0	17.34514	0.877859	4.461435	13.42822	0.267967	904.5074	2.54227	3831.72	0	0	3232.694	1.76711	1065.6245
49	Fendt HYD1	25A	16.21633	0	32.65532	1.627463	2243.371	0.04953	0.463299	12.07257435	94.9577	87.5394	18.05995	1.335134	4.243669	78.34489	0.479708	766.3619	3.043261	2022.534	0.749023	0	9854.577	1.717387	920.531655
50	Fendt HYD1	25B	18.21447	0.0010911	32.22124	1.716357	2502.628	0.04844	0.503599	24.35017828	100.1265	0	16.90043	1.521817	4.161729	2.487111	1.016916	748.5329	3.314222	2249.461	0	0	10517.9	1.814	983.7467851
51	Fendt HYD2	26A	10.08204	0.0079423	45.41335	0.521009	2224.282	0.004453	0.355039	13.25146956	30.55633	0	10.02845	0.626489	2.694967	0	0.26099	754.6221	2.172131	2231.472	0	0	21236.88	1.831904	953.2644298
52	Fendt HYD2	26B	10.96481	0.0100229	46.13947	0.546842	2517.618	0.008919	0.246416	15.51922369	26.24411	0	11.46157	0.603726	2.73094	0	0.120074	777.2336	2.620037	2940.913	0	0	22716.27	1.73006	1052.109138
53	Fendt HYD2	27A	12.63509	0	41.64081	0.549095	2301.485	0.021777	0.347813	8.233042008	23.37919	0	25.6173	0.664844	2.211872	16.92951	0.20773	658.451	2.400629	3591.957	0	0	8085.963	1.678507	1034.915974
54	Fendt HYD2	27B	10.9144	0	41.96767	0.609963	2347.875	0.029556	0.345014	8.46261537	26.91619	0	26.2804	0.660755	2.231961	7.62406	0.161967	661.7636	2.498427	3434.399	0	0	8294.194	1.651424	1071.225003
55	Fendt HYD2	28A	10.82495	0	46.65827	0.637756	2017.129	0.024496	0.290681	9.856335671	23.45362	0	17.1524	0.586075	1.990573	0	0.163835	626.4097	2.457739	3249.884	0	0	11111.24	1.558304	965.5967914
56	Fendt HYD2	28B	11.69475	0	47.01112	0.700143	2256.116	0.031998	0.317355	11.01950185	22.653	0	20.13566	0.639923	2.012408	79.19476	0.105767	644.0396	2.770376	3433.383	0.178359	0	10895.3	1.718306	1088.8616
57	Fendt HYD2	29A	12.34839	0	44.58797	0.605634	2235.461	0.028828	0.293201	9.131185768	19.4522	0	25.42521	0.586399	2.116812	5.956025	0.092827	665.0464	2.541517	3943.637	0	0	8625.605	1.653952	1082.11904
58	Fendt HYD2	29B	10.02124	0	41.43188	0.719907	2272.379	0.027565	0.338981	8.997606897	21.75534	35.83224	25.57296	0.600728	2.108008	92.28602	0.226304	648.7994	2.529893	3113.88	0.131231	0	8383.926	1.623306	1051.079368
59	Fendt HYD2	30A	10.60307	0	44.01251	2.255514	2524.906	0.047712	0.369407	10.64491502	38.33188	0	20.91511	0.746637	2.885946	2.249148	0.18186	752.0899	2.990491	3899.791	0.762249	0	8491.515	1.75147	1127.346637
60	Fendt HYD2	30B	10.76456	0	41.91519	2.319382	2563.148	0.056236	0.373024	10.79826122	37.05802	0	21.18503	0.763493	2.937595	11.163	0.184743	755.6247	3.026668	4207.528	0.073213	0	8515.417	1.712844	1128.908199

Baseline new clean oil sample results from ICP-MS filtered data.

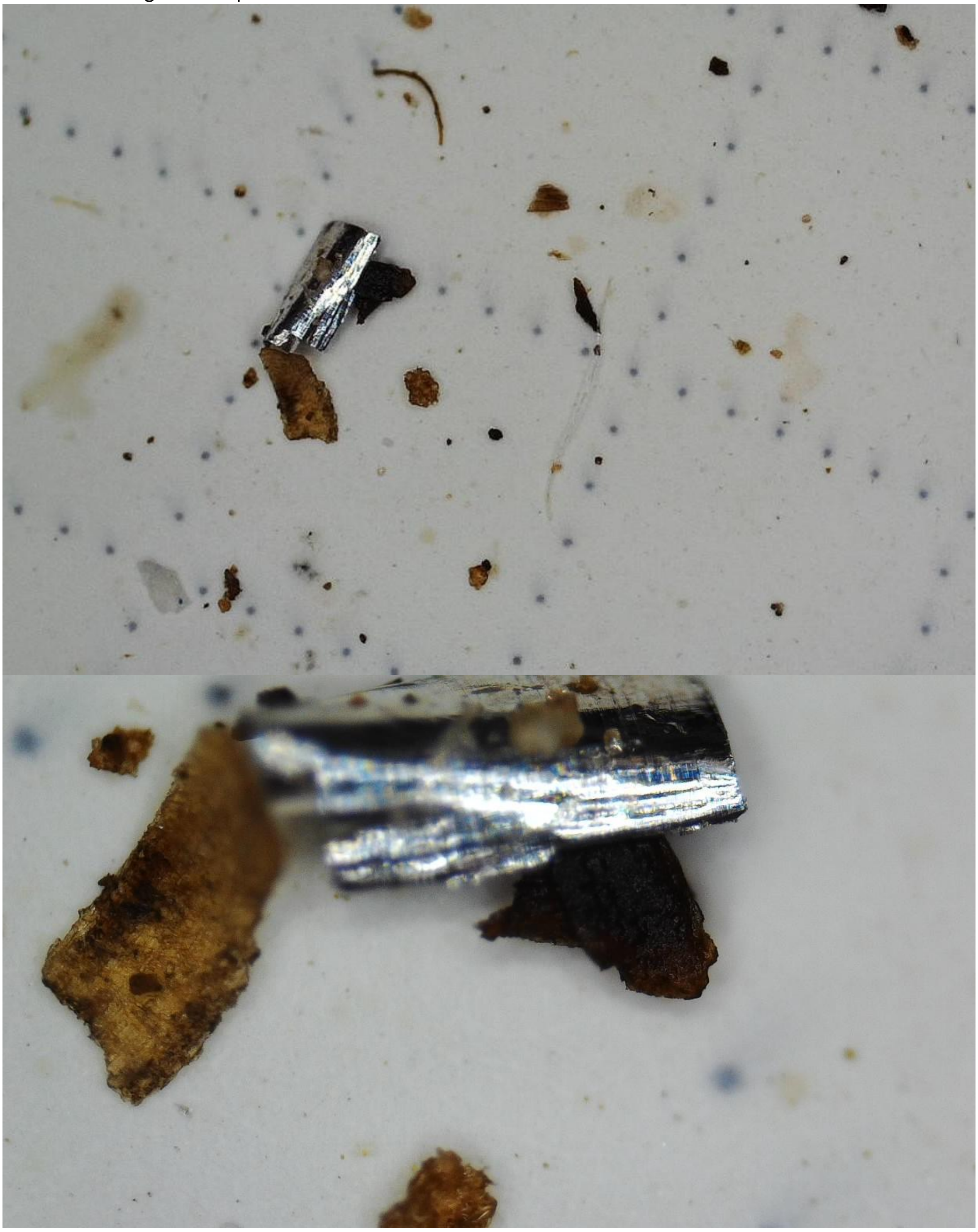
Row	Brand & Tank type	Sample	Al (mg/kg)	As (mg/kg)	B (mg/kg)	Ba (mg/kg)	Ca (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Mo (mg/kg)	Na (mg/kg)	Ni (mg/kg)	P (mg/kg)	Pb (mg/kg)	S (mg/kg)	Se (mg/kg)	Si (mg/kg)	Sn (mg/kg)	Ti (mg/kg)	Zn (mg/kg)
61	New JD HYD and TRA	31A	9.329637	0	109.9578	0.015443	3504.447	0	0.065674	0.066575	0.958311	0	10.55974	0	0.228947	7.07321	0.057287	496.8787	0.006381	5148.754	0	0	0	2.437333	1388.029
62	New JD HYD and TRA	31B	8.630401	0	108.6624	0	3569.076	0	0.09801	0	1.308784	0	9.52017	0	0.146965	3.070538	0.029748	476.9208	0.001783	5195.37	0	0	0	2.300089	1384.868
63	New Fendt TRA	32A	8.191188	0.014914	13.23796	5.288328	3193.596	0.199005	0.088964	0	0.601486	0	29.45026	0.104705	2.648305	2.84639	0.05136	1206.842	0.768722	4628.32	0	0	0	1.936751	1178.906
64	New Fendt TRA	32B	8.818873	0.021925	11.95425	5.218188	3131.938	0.239401	0.078325	0	1.496712	0	28.53689	0.071469	2.768711	1.126462	0.033225	1252.867	0.791307	5091.432	0.435563	0	0	2.014817	1224.364
65	New Fendt HYD1	33A	8.808261	0.007265	15.7097	15.36903	2934.182	0.20185	0.057977	0	2.994596	0	21.38641	0.161429	5.592651	0	0.026003	1166.349	0.59607	4351.284	0.527844	0	0	1.891961	1180.194
66	New Fendt HYD1	33B	10.91499	0.035399	16.00526	15.49705	3014.72	0.174061	0.070931	0.201286	3.660156	0	22.34728	0.060686	5.667711	3.174752	0.014539	1192.123	0.625192	3445.582	0.257977	0	0	1.932545	1193.423
67	New Fendt HYD2	34A	12.30663	0.002862	5.910846	0.153441	2316.718	0	0.026237	0.188552	1.668559	0	11.84038	0	3.046301	0	0.001014	390.6387	0.136896	2419.72	0	0	0	1.54294	1010.277
68	New Fendt HYD2	34B	11.21181	0.015291	5.271505	0.096868	2524.159	0	0.129974	0.124686	3.887767	0	11.86069	0	3.316771	0	0.023917	435.859	0.155429	2539.718	0	0	0	1.755601	1097.188

Appendix 6: Contaminants found in MP Filtri gauze

Returned contamination found in course screen filter inlet of MP Filtri gauze when sent back to manufacturer to be assessed.



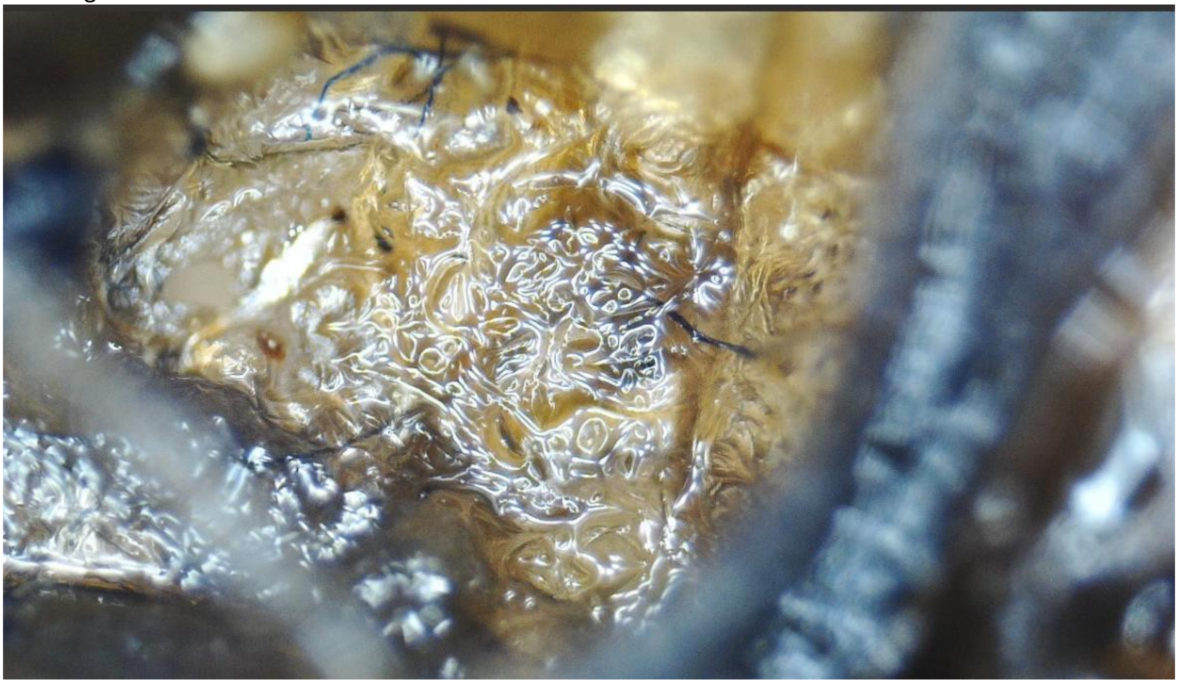
Laboratory microscope imagery of contaminants.
Clear metal filings and crop trash.



Un-known orange contaminant.

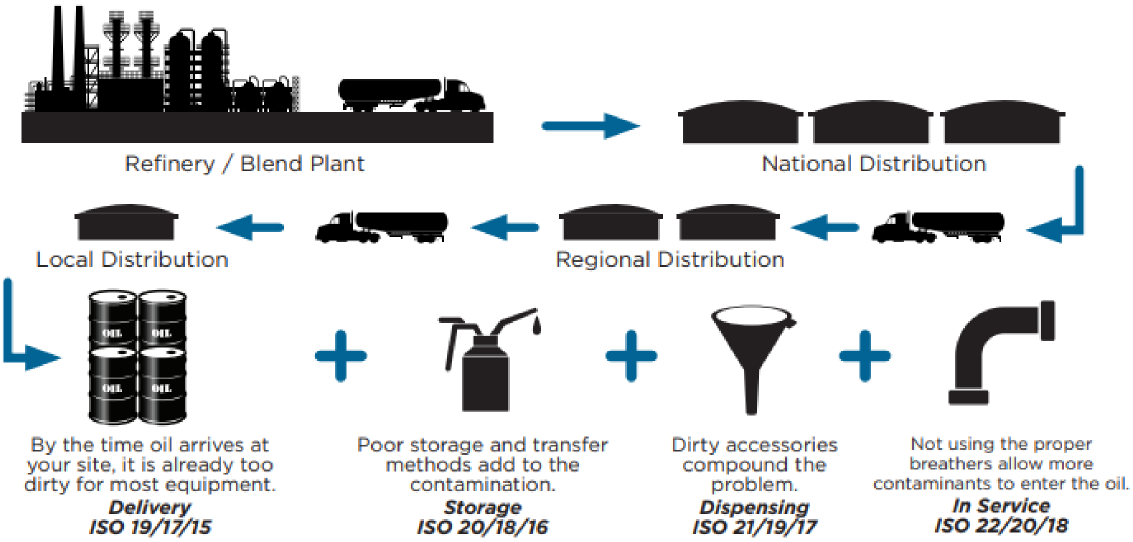
Crop trash and oil sludge

Oil sludge matted



Appendix 7: Oil transportation process from refinery

Oil process from refinery to vehicle, demonstrating the increase in particulate contaminant through transfer and change in ISO 4406 rating. Demonstrating the importance to pre filter before vehicle entry.



(Source: Adapted from Des-Case, 2019)