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Proteinaceous Spirulina Biomass as a Sustainable Drilling Fluid Additive for Lubricity

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Abstract: This study investigates the potential of Spirulina biomass as a lubricating additive for drilling fluid formulations. In this work, this waste protein is evaluated as a lubricant alternative that may decrease the coefficient of friction while improving the rheological profiles and/or reducing fluid loss via permeation in drilling fluids. A processed and dried *Arthrospira platensis* (*Spirulina*) biomass is incorporated into drilling fluid formulations and compared to standard lubricant additives for the drilling fluid properties of lubricity, rheology, and fluid loss. Rheological characterization includes the determination of yield stress, gel strength, and viscosity measurements. The major findings of this study include a friction value reduction of up to 30% and a fluid loss reduction of up to 51% by using 3 vol.% *Spirulina*. Parameters were fit to two rheological models (Bingham plastic and Herschel–Bulkley). After experimentation and analyzing the data gathered, it was determined that *Spirulina* and the *Spirulina*–Coastalube mixture in drilling fluids are good potential candidates as more environmentally benign and cost-effective alternative technologies for drilling fluids for decreasing the coefficient of friction, which results in increasing the lubrication performance of the drilling fluids.

Keywords: *Spirulina*; sustainability; algae biomass; lubricity; drilling fluids; rheology

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1. Introduction

Petroleum and petrochemical industries are continuing to advance toward environmentally benign and sustainable technologies [1–4], and the value of projects that involve sustainable materials will only continue to grow [5]. Based on public disapproval and increasing governmental regulation [6], high-performance water-based mud (WBM) technologies are considered to be attractive alternatives to oil-based mud (OBM) technologies for complex well situations [7]. A major issue while using WBM for drilling processes is the torque that arises from friction within the annular column, which causes equipment and tool wear [8]. To fulfil one of the main drilling fluid objectives of providing lubrication, the coefficient of friction—often simply referred to as lubricity—must be monitored and adjusted. Lubricants can be solid (e.g., nanoparticles or glass beads) or liquid [9]. One solid lubrication additive is graphite, which has the ability to reduce the coefficient of friction while also preventing fluid loss by plugging troublesome formations [10]. Traditionally, solid lubricant performance is less dependent on interactions with the fluid or formation because solid lubricants act as a physical barrier for the drill pipe to roll along. While this is good for resiliency and application versatility, the same properties can cause damage to downhole equipment [11]. Thus, development of liquid lubricants for WBM is essential.

Spirulina protein was identified as a potential sustainable lubricant additive [12]. Most commercially available drilling fluid lubricants are either hazardous or expensive and

sometimes both. *Spirulina* powder could provide an alternative because it is an environmentally friendly bioprocessing byproduct with little to no cost [13]. The utilization of waste algae proteins could allow for a new paradigm of cooperation between conventional petroleum production and emerging biofuel technology [14]. Petroleum production could be made more environmentally benign while enabling co-product development for algal biorefineries to increase profitability [12].

For reference, a Sönmez et al. [11] compared the performance of traditional liquid lubricants (diesel, light oil, and heavy oil) with some newer potential formulations (fatty acid/glycerides, triglyceride/vegetable oil, and polypropylene glycol). At up to three percent by volume, all three new lubricants outperformed the traditional types. With no coefficient of friction (CoF) reduction, diesel was the worst performer, while the fatty acid/glyceride lubricant exhibited the most CoF reduction at 60%. The study also looked at the performance of combinations of the fluids, which showed an optimum formulation of 3 percent light oil with 2 percent of the triglyceride/vegetable oil-based lubricant. However, it should be noted that this would not be an appropriate mixture for areas where using petroleum oils in drilling fluid is prohibited or heavily regulated [11].

The bentonite replacement results from the previous study [12] showed that *Spirulina* powder increased viscosity, decreased fluid loss, and decreased the coefficient of friction. Though the increase in viscosity was not enough to replace bentonite gel outright, the decrease in the coefficient of friction led to further investigation of the performance of the *Spirulina* powder as a drilling fluid lubricant. Using the same formulation as the control from the previous study [12]—with the mid-range sodium hydroxide concentration and bentonite gel as the viscosifier—in this study, the *Spirulina* powder was tested against diesel and two commercially available lubricants. One is a high-performance lubricant that contains Environmental Protection Agency (EPA)-regulated components [15] for use in areas such as the Gulf of Mexico, while the other does not contain EPA-regulated components [16]. One (1), two (2), and (3) volume percent concentrations for each lubricant were tested. Though lubricity is the main focus, all samples were tested for high-pressure + high-temperature fluid loss, rheology, and the coefficient of friction (CoF) to evaluate any secondary benefits or drawbacks.

2. Experimental Methods and Data Collection

Many of the methods and materials follow from the referenced study [12] and a published patent [17].

2.1. Materials and Reagents

The lubricants used in this study, specifically diesel and Coastalube (a synthetic polyalphaolefin), were purchased from Sun Coast Resources, Inc. in Austin, TX, USA, and Sun Drilling Products Corp. in Belle Chasse, LA, USA, respectively. HDL Plus was also provided by National Oilwell Varco in Houston, TX, USA. The base drilling fluid composition is comprised of the following materials that were assembled from a preceding publication [12].

Acetar Bio-Tech Inc. (Xi'an, China) supplied the Spirulina blue-green cyanobacteria biomass, which had a protein content of 62.2 wt%. We bought sodium hydroxide (caustic soda) from Axiall, LLC in Houston, TX, USA. Barite (barium sulfate) was acquired from Excalibar, LLC in Dallas, TX, USA, while lignite (humic acid—leonardite) and bentonite (sodium bentonite) were acquired from Cetco/American Colloid in Hoffman Estates, Illinois. A tannin-based deflocculant (Desco) was purchased from Drilling Specialties in The Woodlands, TX, USA. Xanthan gum (polymer) and defoamer (glycol, silicone,

and alcohol-based constituents) were supplied by National Oilwell Varco in Houston, TX, USA [12].

2.2. Sample Preparation of Drilling Fluids

Aside from the additions of lubricant additives, the base drilling fluid preparation in this study coincides with a previous study [12] and patent [17]. Table 1 lists the ingredients of the base drilling fluid, which includes xanthan gum, barite, defoamer, lignite, and algal protein or bentonite as an added viscosifier, where the additive concentrations are measured on the basis of lbs/bbl. Using a five-spindle, single-speed multimixer, all materials were combined in a stainless steel mixing cup. The samples were then matured in glass jars with the implementation of a roller oven [12].

Table 1. Components of base drilling fluid, functions, and concentrations [12].

Component	Function	Concentration (lb/bbl)
Tap water	Base fluid	Varied
Gel NT (bentonite)	Viscosifier	20.0
Organic polymer	Defoamer	0.99
Caustic soda	pH modifier	0.50
Lignite	Thinner	2.00
Desco	Deflocculant	2.00
Xanthan gum	Viscosifier	0.50
Barite	Weighting agent	Varied
Lubricant—varied	Lubrication	See Table 2

Note: 1 lb/bbl is equal to 1.29 kg/L.

Table 2. List of fluids studied with the lubricant added to base formulation.

Fluid ID.	Lubricant Type	Concentration (vol.%)
1	None	0.0
2	*Spirulina*	1.0
3	*Spirulina*	2.0
4	*Spirulina*	3.0
5	Diesel	1.0
6	Diesel	2.0
7	Diesel	3.0
8	HDL Plus	1.0
9	HDL Plus	2.0
10	HDL Plus	3.0
11	Coastalube	1.0
12	Coastalube	2.0
13	Coastalube	3.0
14	*Spirulina* and Coastalube	0.5 and 0.5
15	*Spirulina* and Coastalube	1.0 and 1.0
16	*Spirulina* and Coastalube	1.5 and 1.5

The lubricant type and concentration variations can be seen in Table 2. A lab barrel is roughly equivalent to 350 milliliters, where the density units can be either pounds per barrel or grams per 350 milliliters.

Aside from water, barite, and the lubricant, all of the additive concentrations were maintained constant. The kind and concentration of the lubricant were modified, and only the amount of barite and water was changed to guarantee a final fluid density of ten pounds per gallon. The appropriate volume of water was added to the mixing vessel, and then the Gel NT was gradually added during mixing. After that, the defoamer was added, and the gel was mixed for thirty minutes to allow it to hydrate. The mixture considerably

thickened and stopped stirring when the caustic soda was introduced. At this stage, Desco and lignite were introduced to thin the fluid. After 10 min, xanthan gum was added to the mixture, followed by barite after another 5 min. After stirring for an additional fifteen minutes, the mud was separated into stainless steel malt cups with volumes equivalent to 1 lab barrel each. Using a syringe, the amount of fluid that would be replaced with lubricant was removed. At the specified volumes, one chosen lubricant was added to each sample mud (the weight of the algae was determined using a specific gravity measurement of 1.816). After that, the mud was put into a glass jar and heated to 150 °F (65.5 °C) for sixteen hours in a roller oven to undergo hot rolling, or aging [17].

2.3. Rheology

Using an OFITE Model 900 Viscometer [18] and following the manufacturer's operation instructions, all of the rheological measurements were performed in compliance with API RP 13B-1. The fluid was hot-rolled and then mixed for five minutes on a multimixer before being poured into the sample cup for the viscometer. The bob was dipped into the sample and oriented to the sleeve's submersion line. The standard viscometer readings for drilling fluids were obtained by heating the sample to 120 °F (49 °C) and taking dial readings at speeds of 600, 300, 200, 100, 6, and 3 rpm [18]. Equations (3) and (5) were utilized to compute the yield point and plastic viscosity, respectively. Following a ten-second pause on the viscometer's rotation, the gel strength was measured at 3 rpm via the maximum dial reading. We performed this again for both ten- and thirty- minute timestamps [12].

Bingham plastic is a typical two-parameter model for non-Newtonian fluids. Since the parameters of the Bingham plastic model can be readily determined without the need for a computer or complicated algorithm, it is the standard way of characterizing these fluids under field conditions. Therefore, the Bingham plastic model was computed for every mud sample in this study. Equation (1) illustrates how to apply the model with the yield point (YP) and plastic viscosity (PV) values that are determined using Equations (3) and (5), respectively. Although the units in this version of the equation are dial readings (°), they serve as estimates in pounds per hundred square feet ($lb_f/100\ ft^2$) for the YP and centipoise (cP) for the PV [12,19].

$$\tau = YP + \frac{PV \times \dot{\gamma}}{511} \tag{1}$$

$$PV\ [\text{cP}] = \left(\frac{PV[^\circ]}{511\ \text{s}^{-1}}\right) \times \left(\frac{511\ \text{mPa}}{^\circ}\right) \times \left(\frac{cP}{\text{mPa·s}}\right) \cong PV[^\circ] \tag{2}$$

$$PV = R_{600} - R_{300} \tag{3}$$

$$YP\left[\frac{\text{lbf}}{100\text{ft}^2}\right] = YP[^\circ] \times 1.067 \cong PV[^\circ] \tag{4}$$

$$YP = R_{300} - PV \tag{5}$$

While Bingham plastic is frequently employed to describe the rheological characteristics of drilling fluids, research has indicated [20] that the three-parameter Herschel–Bulkley model, represented by Equation (6), provides a more accurate representation of the behavior of water-based bentonite drilling fluids. Based on the gathered rheological data, Equations (7)–(9) were utilized to compute the Herschel–Bulkley parameters, which include yield stress, the flow behavior index, and the consistency factor, based on the rheology data [12].

$$\tau = \tau_y + k\dot{\gamma}^n \tag{6}$$

$$\tau_y \cong 2 \times R_3 - R_6 \tag{7}$$

$$n = 3.32 \times \log_{10}\left(\frac{R_{600} - \tau_y}{R_{300} - \tau_y}\right) \quad (8)$$

$$k = \frac{R_{300} - \tau_y}{511^n} \quad (9)$$

2.4. Fluid Loss

Using an OFITE 4-Unit HTHP Filter Press [19,21], all of the fluid loss measurements were performed in compliance with API RP 13B-1 and following the manufacturer's operation instructions. After setting the thermocouples to 250 °F (121 °C) within the filter press, the sample was added to the pressured collection cell until it was 0.5 inches (13 mm) from the top. The cell was covered with filter paper before the cap was put on, and all the screws and valve stems were tightened. The filter paper side of the cell was placed downward into the jacket's preheated apparatus. In order to provide back pressure during heating, the top valve stem was opened after the bottom and top regulators were set to 100 psi (689 kPa). Following the cell's temperature rise, the bottom valve was opened to initiate filtering at a 500 psi (3.447 MPa) differential pressure, with the top regulator being set at 600 psi (4.137 MPa). After the experiment commenced for 30 min, the filtrate was removed from the condenser once the bottom valve stem was closed. In order to scale up to a typical API filter's size, the measured volume of the filtrate was doubled and regarded as the total fluid loss for this experiment [17].

2.5. Lubricity

An OFITE extreme pressure and lubricity apparatus [22] was utilized for all of the lubricity measurements in compliance with the manufacturer's operation instructions. The OFITE lubricity meter was calibrated before each set of drilling fluids was tested. The calibration was performed by immersing the meter's ring and block in deionized water and allowing it to rotate at 60 rpm. Equation (10) was used to find the correction factor (CF) [12].

Following the calibration check, the ring and block were submerged in the first drilling fluid-filled sample container. Once the reading stabilized, the torque was set to zero. Then, a new reading was taken after 150 inch-pounds (16.9 N·m) of torque was applied to the sample container and allowed to sit for five minutes. Using a torque wrench reading 150 inch-pounds and a torque shaft lever arm length of 1.5 inches (3.8 cm), Equation (11) calculates the coefficient of friction (CoF). Using both Equations (10) and (11), Equation (12) calculates a corrected version of the coefficient of friction for the tested drilling mud samples. The percent change in the coefficient of friction, as given in Equation (13), is a better metric and makes comparisons between various studies and lubricants [12].

$$CF = \frac{34.0}{Meter\ Reading\ for\ Water} \quad (10)$$

$$CoF = \frac{Torque\ Reading}{\left(\frac{150\ \text{in}-\text{lb}}{1.5\ \text{in}}\right)} = \frac{\tau}{100\ \text{lb}} \quad (11)$$

$$CoF_{corr.} = CoF \times CF \quad (12)$$

$$\%_{change} = \frac{CoF - CoF_{base}}{CoF_{base}} \times 100 \quad (13)$$

3. Results and Discussion

The same base fluid was used in all of the experiments in the publication, with the type of lubricant and concentration being varied. In order to reduce variations from base

formulations, a baseline formulation was run with no lubricant for each batch. The results were calculated as the relative change from the baseline sample.

3.1. Rheology

3.1.1. Bingham Plastic Model

Figures 1 and 2 show the PV and YP data for each of the fluid samples, while the data in Figures 3 and 4 show the PV and YP percent changes from the baseline (control) fluid. The error bars indicate the standard deviation of the results from triplicate measurements. The two fluids with added *Spirulina* and *Spirulina*–Coastalube (CL) had the most significant influence on the PV and YP. HDL Plus exhibited a lesser effect. Compared to the control fluid, the fluid with a 3% *Spirulina* concentration exhibited increases of PV by nearly 380% and YP by 575%. On the other hand, the *Spirulina*–CL mix at a 3% concentration effected smaller increases of 175% for the PV and 205% for the YP. It is worth noting that foaming was apparent at three percent *Spirulina* but was not an issue at the same concentration of the *Spirulina*–CL mix.

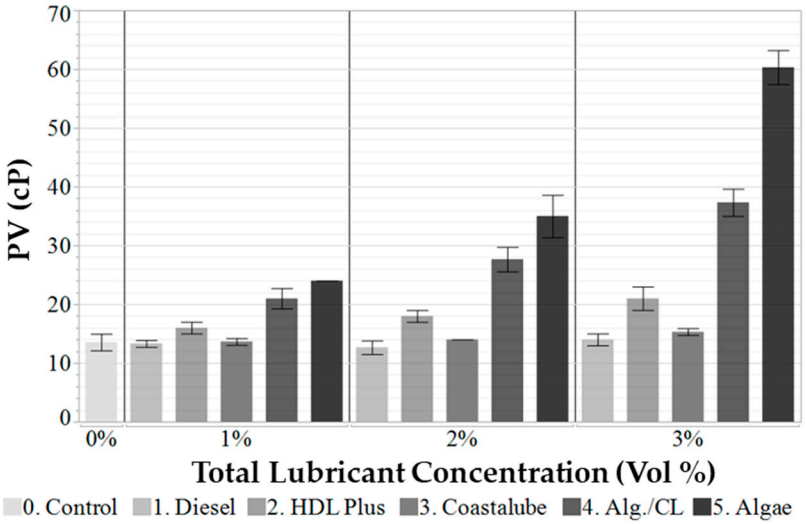


Figure 1. Plastic viscosity (PV) raw data vs. lubricant type and concentration [17].

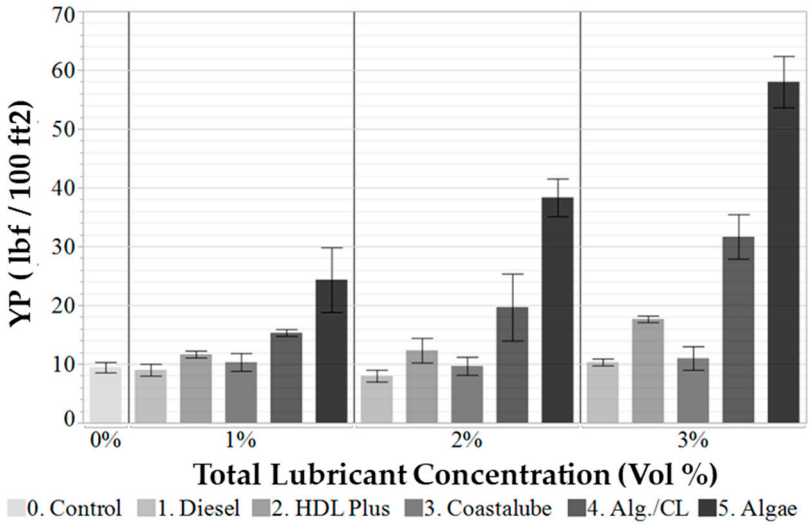


Figure 2. Yield point (YP) raw data vs. lubricant type and concentration [17]. Note: 1 lb_f/ft^2 = 47.9 Pa.

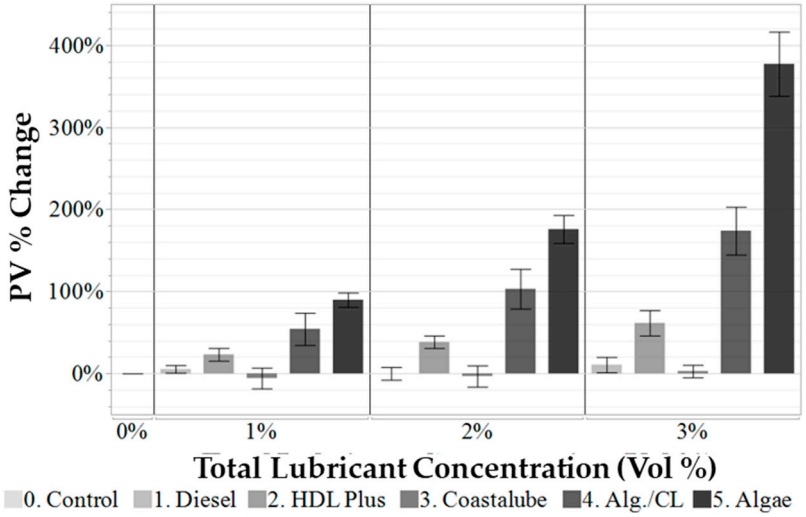


Figure 3. Plastic viscosity (PV) percent change vs. lubricant type and concentration [17].

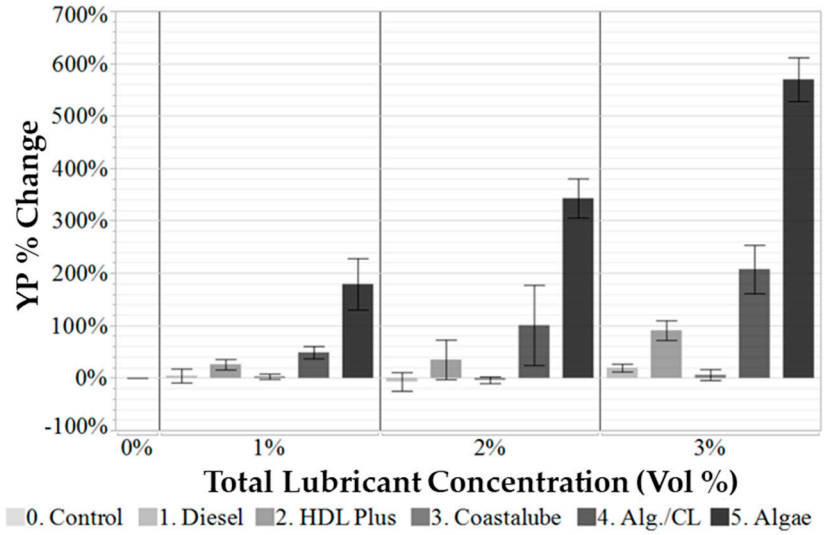


Figure 4. Yield point (*YP*) percent change vs. lubricant type and concentration [17].

While it is not the most accurate model across the rheological profile of a drilling fluid, the parameters from the Bingham plastic are the most commonly used parameters when characterizing rheological properties. Generally, in traditional drilling fluid applications, an increased plastic viscosity and yield point are desired; however, there are cases where this is not true. Increasing the yield point can shift the flow mechanism from turbulent flow to laminar flow, which is desirable for improved cutting transport and an improved rate of penetration (RoP). Higher-viscosity fluids do contribute to increases in the equivalent circulating density (ECD), which can be limited in some cases by the rig circulation system equipment. If a rig runs into an ECD limit, it would be better to use a thinner fluid at viscous flow conditions. It is best to avoid the unstable transition region between laminar and turbulent flow, where the flow regime can become unpredictable [23].

Based on these results, the *Spirulina* addition to the drilling fluid increases the yield point and plastic viscosity significantly more than diesel or either lubricant tested. This is partially due to the *Spirulina* being a powder rather than a liquid but also because of the nature of the protein chains in the *Spirulina* powder to unfold in the presence of a strong base such as sodium hydroxide. Studies have shown that heat and pH can affect the viscoelastic properties of the proteins and form gels, which offers a potential cause for the viscosity increase [24]. In a system where a low viscosity is necessary or desired, the

Spirulina powder may not be a good fit as a lubricant; however, in such a case, the plastic viscosity and yield point increases could be reduced by using the *Spirulina*–CL mix instead of only *Spirulina*.

3.1.2. Herschel–Bulkley Model

Table 3 displays the fitted parameter averages between the Herschel–Bulkley and Bingham plastic models. To have a better idea of the impact of each lubricant, the control values are subtracted from the given parameter to give the delta (Δ) values used in the bivariate significance fitting. The levels of significance between the lubricant concentration and the Herschel–Bulkley parameters are displayed in Table 4, which is based on bivariate plots with *p*-value data—yield stress (Figure 5A–E), the consistency factor (Figure 6A–E), and the flow behavior index (Figure 7A–E). Based on this analysis, diesel and Coastalube do not have a significant impact ($p > 0.05$) on any of the Herschel–Bulkley parameters. HDL Plus has a significant effect ($0.01 < p < 0.05$) on the consistency factor (k) only. Though the concentration of the *Spirulina* with and without Coastalube has a very significant ($p < 0.01$) effect on the yield stress (τy), only the *Spirulina* has a very significant fit ($p < 0.01$) with the flow behavior index (*n*) as well.

Table 3. Fitted Herschel–Bulkley parameters for fluids studied.

Fluid ID	Lubricant Type	Concentration (vol.%)	τ_y	k	*n*
1	None	0.0	1.778	0.254	0.712
2	*Spirulina*	1.0	6.000	0.763	0.649
3	*Spirulina*	2.0	14.000	0.928	0.668
4	*Spirulina*	3.0	25.667	1.022	0.723
5	Diesel	1.0	1.667	0.239	0.720
6	Diesel	2.0	0.333	0.269	0.698
7	Diesel	3.0	1.667	0.303	0.693
8	HDL Plus	1.0	2.667	0.297	0.713
9	HDL Plus	2.0	3.000	0.295	0.732
10	HDL Plus	3.0	3.333	0.537	0.672
11	Coastalube	1.0	1.333	0.341	0.682
12	Coastalube	2.0	1.333	0.292	0.704
13	Coastalube	3.0	1.667	0.324	0.697
14	*Spirulina* and Coastalube	0.5 and 0.5	3.333	0.400	0.709
15	*Spirulina* and Coastalube	1.0 and 1.0	5.333	0.464	0.735
16	*Spirulina* and Coastalube	1.5 and 1.5	10.000	0.719	0.707

Table 4. Significance of H-B parameters vs. concentration of lubricant from least squares fit.

Lubricant Type	τ_y	k	*n*
Spirulina	VS	X	VS
Diesel	X	X	X
HDL Plus	X	S	X
Coastalube	X	X	X
Spirulina and Coastalube	VS	X	X

VS: very significant; S: significant; X: not significant.

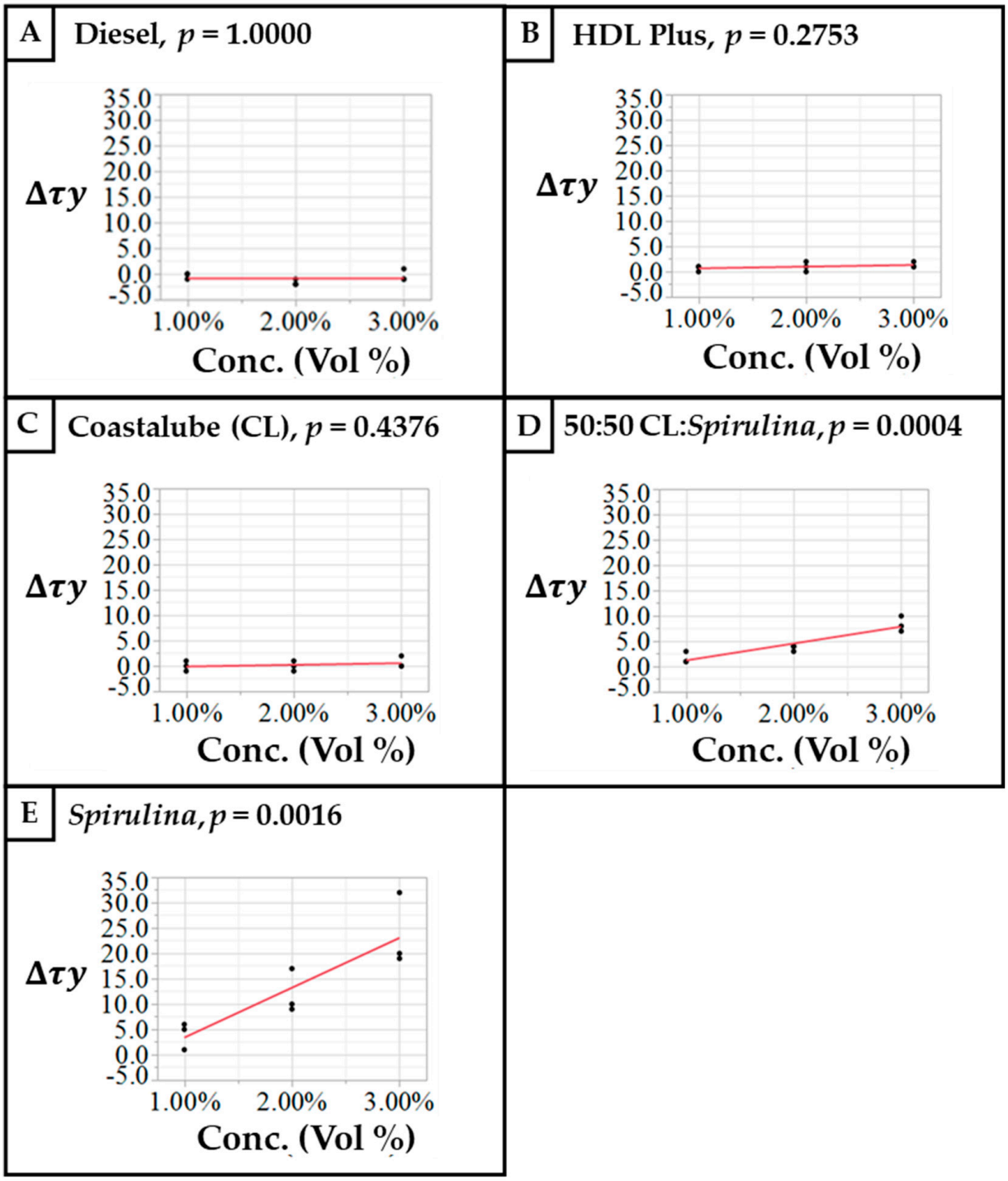


Figure 5. Bivariate fit of Δτy vs. different lubricant concentrations of (**A**) diesel, (**B**) HDL Plus, (**C**) Coastalube, (**D**) 50:50 Coastalube–*Spirulina*, and (**E**) *Spirulina*. The points represent calculations from each tested fluid along with a red, best-fit line for the data.

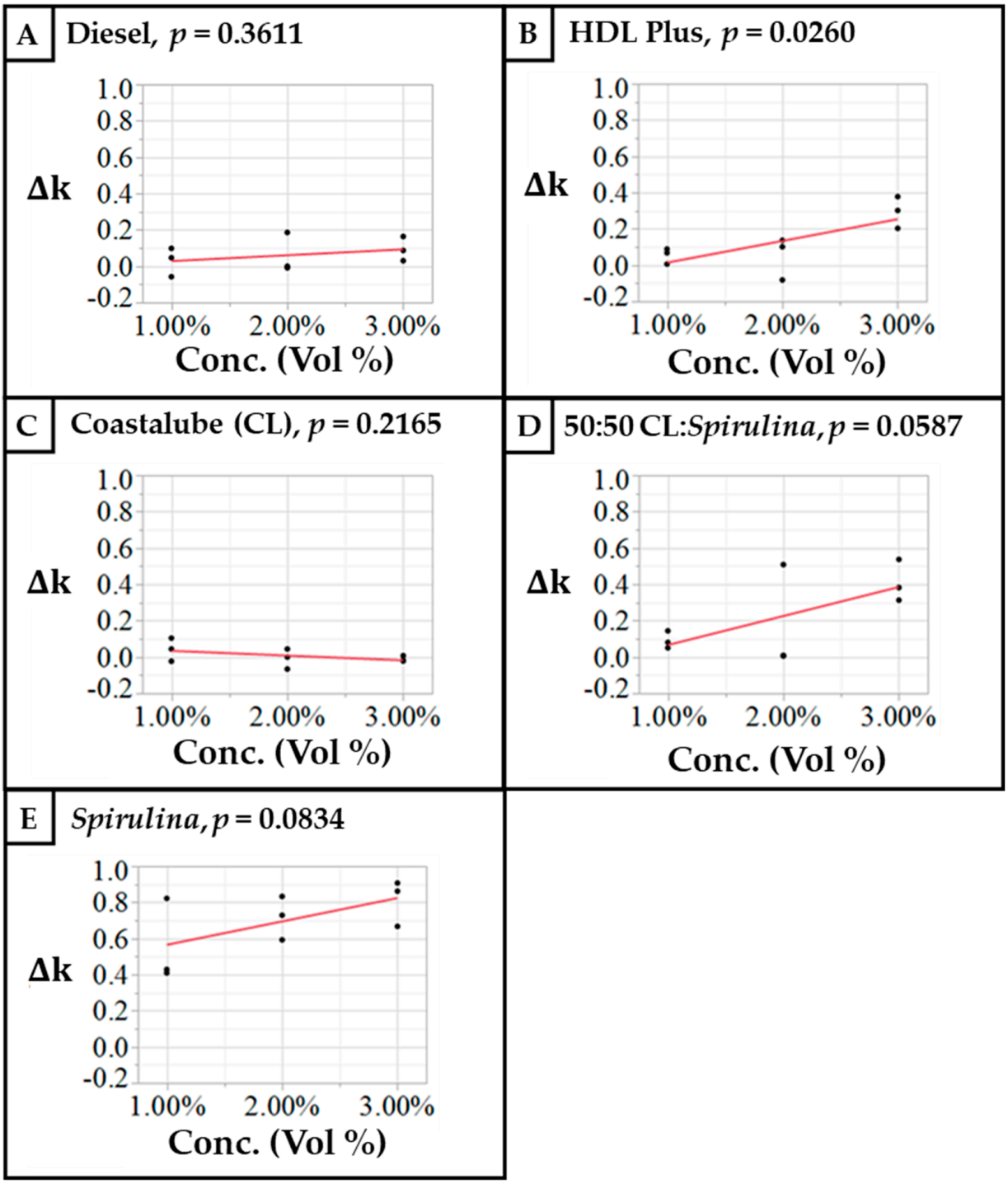


Figure 6. Bivariate fit of Δk vs. different lubricant concentrations of (**A**) diesel, (**B**) HDL Plus, (**C**) Coastalube, (**D**) 50:50 Coastalube–*Spirulina*, and (**E**) *Spirulina*. The points represent calculations from each tested fluid along with a red, best-fit line for the data.

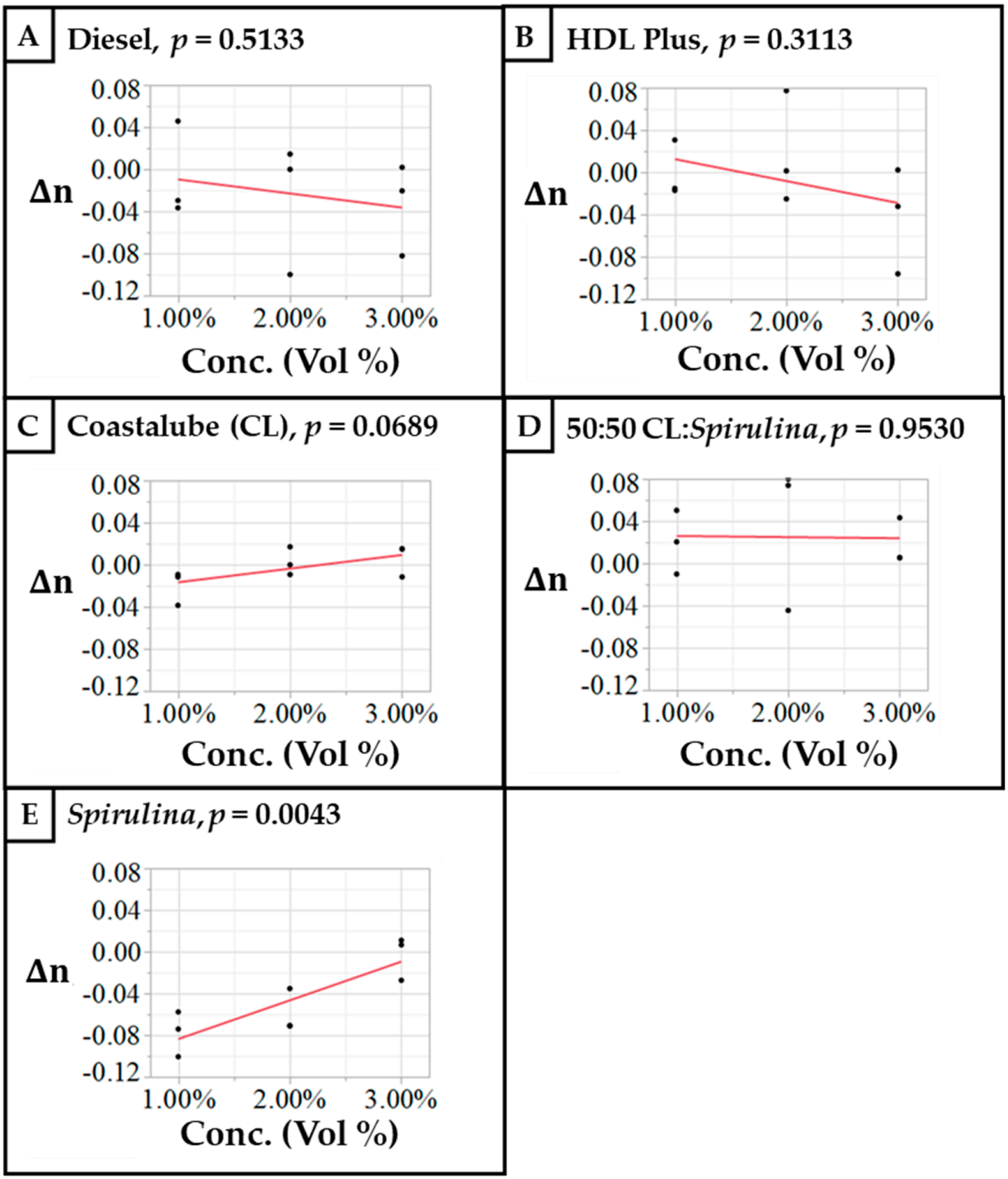


Figure 7. Bivariate fit of Δn vs. different lubricant concentrations of (**A**) diesel, (**B**) HDL Plus, (**C**) Coastalube, (**D**) 50:50 Coastalube–*Spirulina*, and (**E**) *Spirulina*. The points represent calculations from each tested fluid along with a red, best-fit line for the data.

The results from fitting the Herschel–Bulkley model were comparable to that of the Bingham plastic model. The addition of *Spirulina* (with or without Coastalube) significantly affected the drilling fluid yield stress values. Since the Coastalube alone had no significant effect on any of the H-B parameters, it is logical that the yield stress effect seen in the mixture is due to the *Spirulina* and not the Coastalube. This hypothesis is backed by the similarity in the yield stress values of the two (2) percent *Spirulina*–CL mix and the one (1) percent *Spirulina*. Both fluids have the same *Spirulina* content and an average yield stress of 5.33 and 6.00, respectively.

3.1.3. Gel Strength

Gel strength assesses a fluid's capacity to sustain its viscosity after a short duration of static rest. The results of the ten-second gel strength (Figure 8), ten-minute gel strength (Figure 9), and thirty-minute gel strength (Figure 10) are shown below. Though the gel strength readings were measured in viscometer units—degrees of deflection (°)—they are often reported in units of pounds force per hundred square feet ($lb_f/100\ ft^2$) because the conversion is nearly one (1). Figures 11–13 show the percent change in each of these terms relative to the control fluid. The error bars indicate the standard deviation of the results from triplicate measurements. The gel strength results are mostly unaffected by the presence of diesel or Coastalube, though HDL Plus shows a slight benefit and the *Spirulina* and *Spirulina*–Coastalube samples show a larger increase. The relative sample gel strength increase may appear to be very high as a result of the control fluid's low gel strength. The increase in gel strength from only adding *Spirulina* ranged from approximately 300% to nearly 2000%, while the *Spirulina*–CL fluid increased gel strength by 100% and 750% at the same loading.

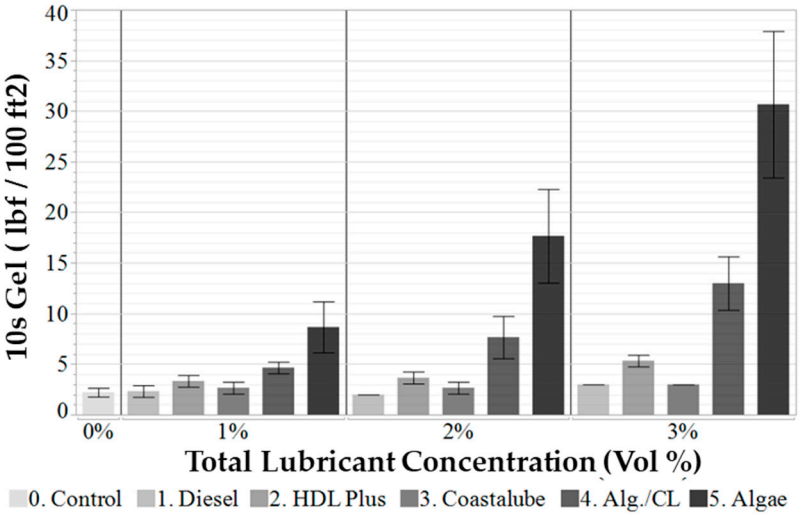


Figure 8. Ten-second gel raw data vs. lubricant type and concentration [17]. Note: 1 lb_f/ft^2 = 47.9 Pa.

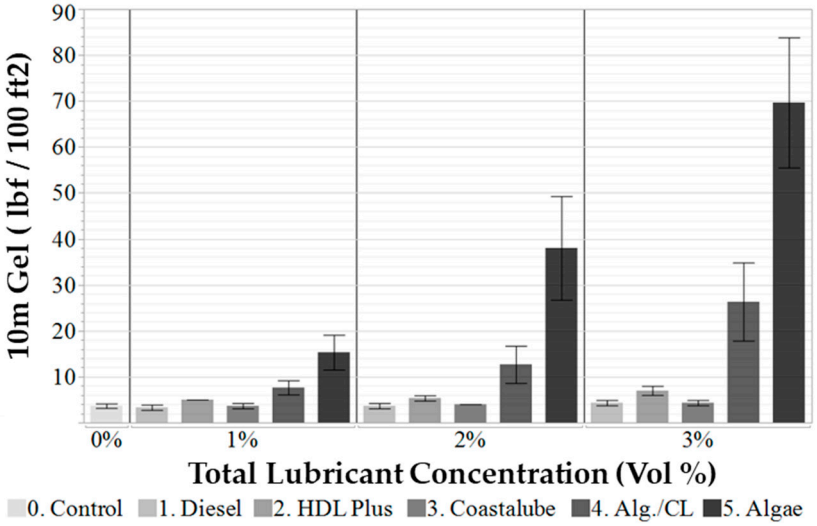


Figure 9. Ten-minute gel raw data vs. lubricant type and concentration [17]. Note: 1 lb_f/ft^2 = 47.9 Pa.

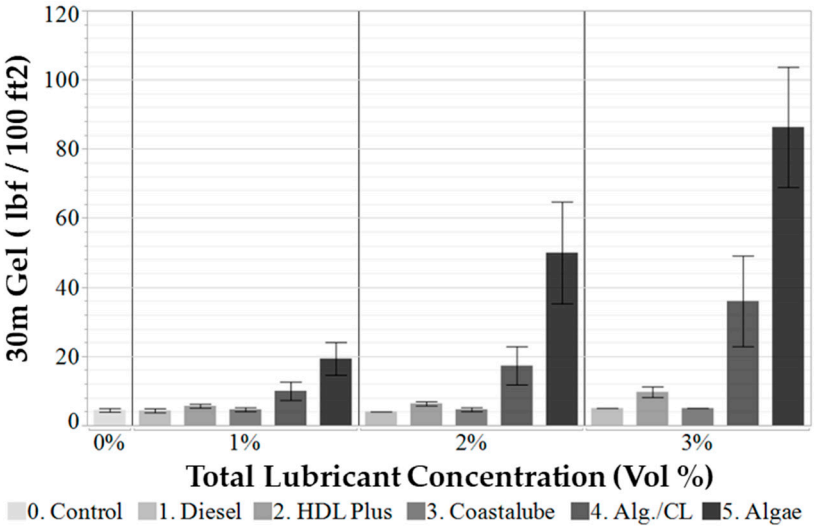


Figure 10. Thirty-minute gel raw data vs. lubricant type and concentration [17].

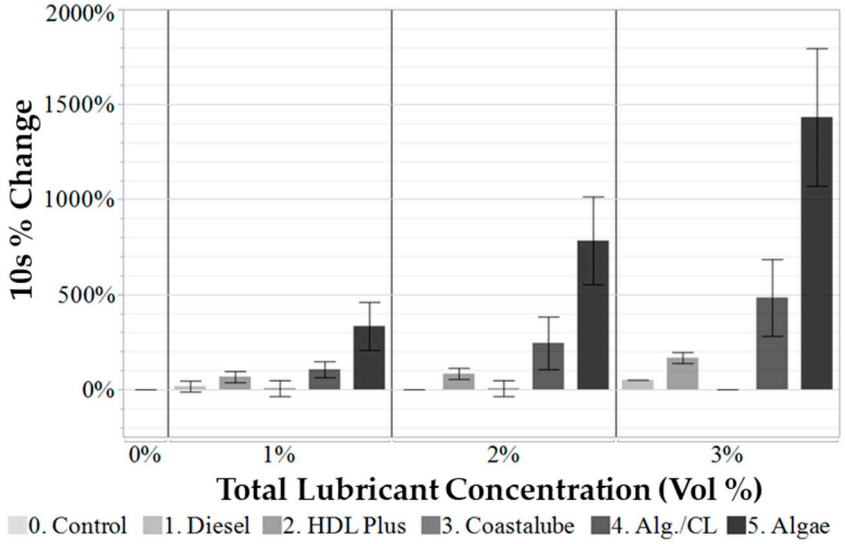


Figure 11. Ten-second gel percent change vs. lubricant type and concentration [17].

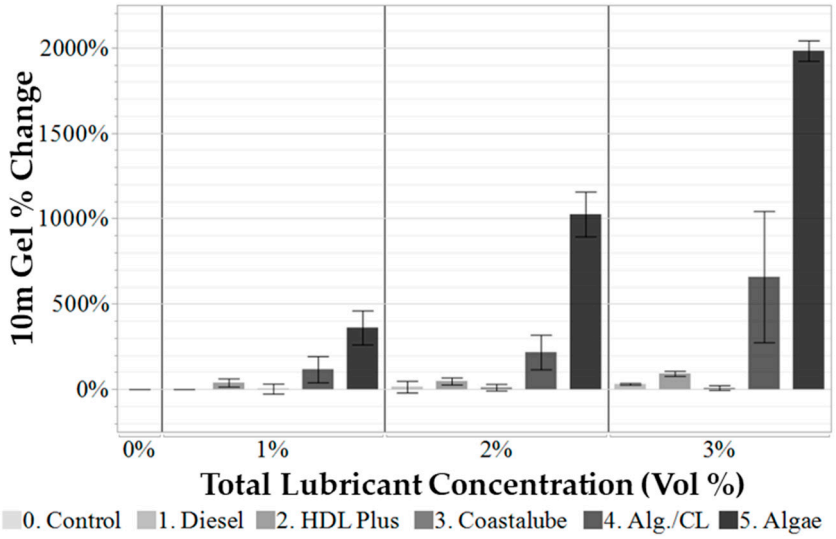


Figure 12. Ten-minute gel percent change vs. lubricant type and concentration [17].

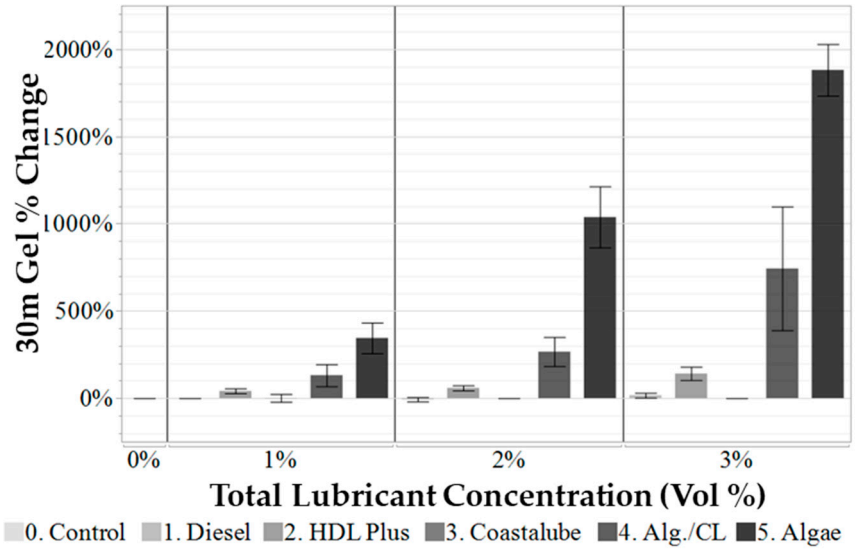


Figure 13. Thirty-minute gel percent change vs. lubricant type and concentration [17].

For all three time intervals that gel strength measurements were taken, the *Spirulina* gel strength was significantly higher than any of the other tested lubricants, although the *Spirulina*–CL mix also showed an increase in this value. Gel strength is important to a drilling fluid because it helps to maintain the suspension of cuttings and other solids when circulation is stopped, which can often be a problem area for water-based fluids. In most applications where a lubricant is needed, such as highly deviated or small-diameter wells, there will also be a need for a fluid with a proper cutting suspension to reduce the risk of differential sticking. The potential downside is a situation in which equivalent circulating density (ECD) is an issue. A fluid with a higher gel strength will put greater demand on circulating equipment when restarting circulation, and the drastically higher values of the *Spirulina* powder fluid could be a problem. However, this can again be mitigated by choosing to use the mix of *Spirulina* and Coastalube instead of just *Spirulina*.

3.2. Fluid Loss

The formulation's ability to reduce or mitigate fluid loss to permeable rock formations can be evaluated through high pressure + high temperature filtrate testing. The results of the filtrate tests, as displayed in Figures 14 and 15, show the percentage of change in filtrate volume from the control fluid sample [19]. The error bars indicate the standard deviation of the results from triplicate measurements. With fluid loss reductions of 28% and 52% at the low and high loading levels, the *Spirulina* powder exhibited the greatest performance across all concentrations. One may note that at concentrations of 2% lubricant, the *Spirulina* and *Spirulina*–CL fluids had nearly identical behaviors, despite the *Spirulina*–CL fluid having 50% less *Spirulina* in the composition.

As most lubricants are thin liquids with little to no solid content, it is not typical to see a major effect on the drilling fluid's performance on its fluid loss capabilities [25]. Though some reduction in filtrate volume was observed for diesel, HDL Plus, and Coastalube, the overall results are within the margin of error, and no clear trend can be found between the concentration of lubricant and fluid loss. In the samples containing *Spirulina*, however, there is a further reduction in fluid loss with each increase in concentration. The mix does not perform as well as the *Spirulina* alone, which could mean that the fluid loss reduction is mainly due to the increase in solids content. The fluid loss reduction from this study is compared with other studies from the literature in Table 5. Though this is not the main

driver or performance indicator for most lubricants, it is an added benefit that can help to increase the marketability and value of *Spirulina* as a solution to multiple problems.

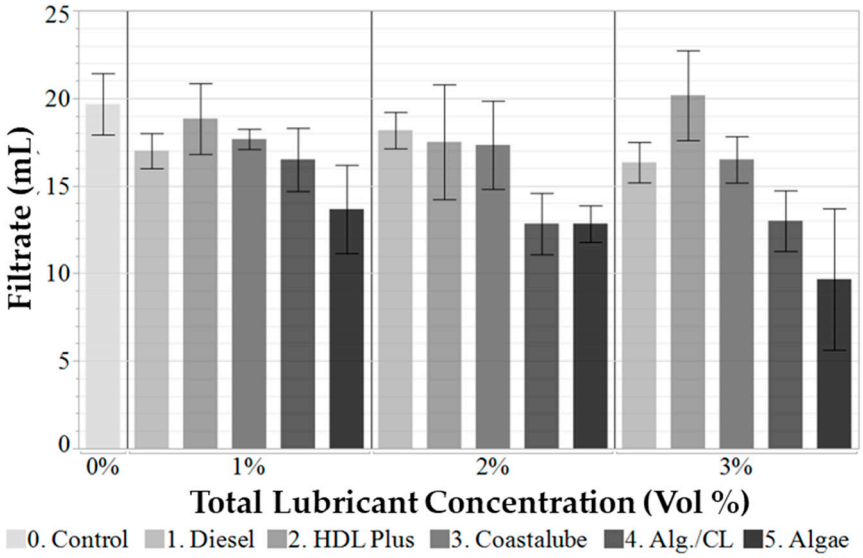


Figure 14. High-pressure, high-temperature filtrate volume vs. lubricant type and concentration [17].

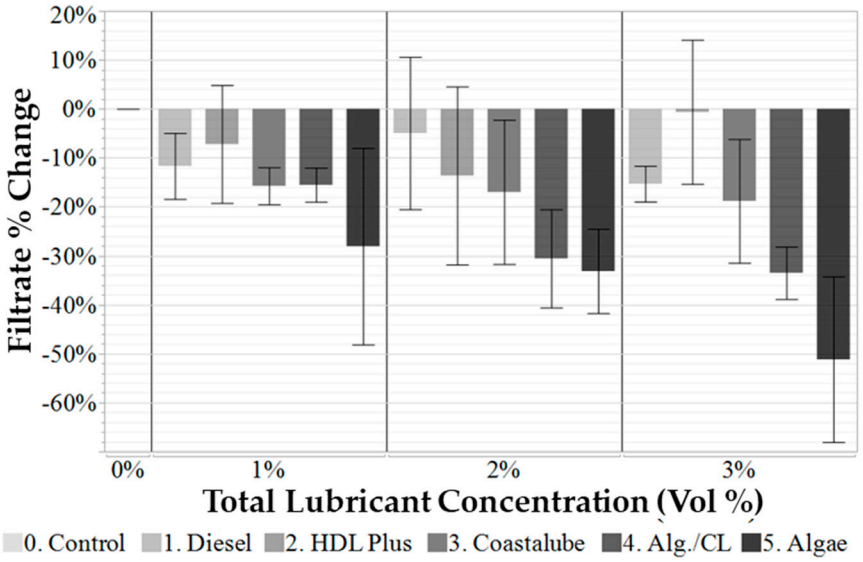


Figure 15. High-pressure, high-temperature filtrate volume change vs. lubricant type and concentration [17].

Table 5. Comparison of HTHP fluid loss reduction in this study with values from the literature.

Lubricant Type	Source	Concentration (vol.%)			
		<1%	1%	2%	3%
Diesel	-	-	−12%	−5%	−15%
HDL Plus	-	-	−7%	−14%	−1%
Coastalube	-	-	−16%	−17%	−19%
Spirulina and Coastalube	-	-	−16%	−31%	−33%
Spirulina	-	-	−28%	−33%	−51%
Date Seed Powder	[26]	-	−60%	-	-
Iron-oxide Nanoparticles	[27]	−28%	-	-	-
Iron-oxide Clay Hybrid	[27]	−47%	-	-	-
Aluminosilicate Clay Hybrid	[27]	−20%	-	-	-

3.3. Lubricity

The reduction in a fluid's coefficient of friction is a highly effective means to assess the lubricating properties of a fluid. Figure 16 displays all of the corrected coefficient of friction reduction values for each of the lubricants, which were calculated using Equation (12). The percent change of these values were calculated using Equation (13) and shown in Figure 17. The reported values are averaged from triplicate measurements, and the standard deviation is shown in error bars. HDL Plus exhibited the best coefficient of friction reduction at every concentration. However, one should note the Spirulina–CL fluid outperformed the Coastalube fluid at one percent and two percent concentrations. Across all concentrations, the *Spirulina*–CL mix performed as well as the *Spirulina* fluid despite the *Spirulina*–CL fluid having 50% less *Spirulina* in the composition.

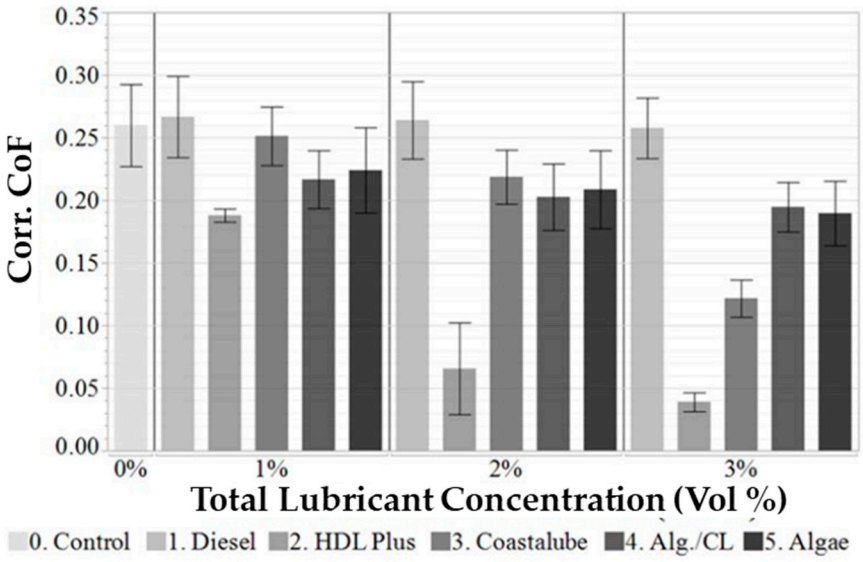


Figure 16. Corrected coefficient of friction (CoF) results vs. lubricant type and concentration [17].

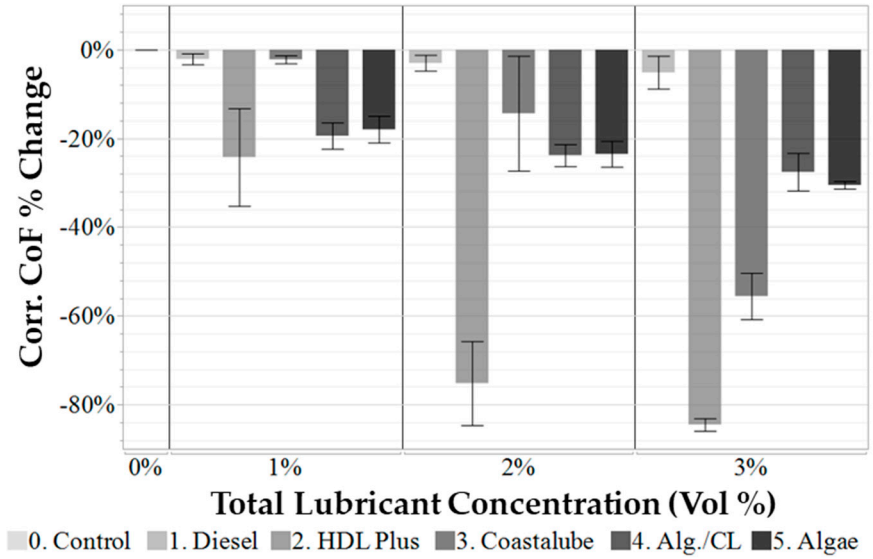


Figure 17. Corrected coefficient of friction (CoF) change vs. lubricant type and concentration [17].

The main focus of this study was to evaluate the lubrication performance of Spirulina powder as an additive for drilling fluids, primarily as assessed through the coefficient of friction. Though the HDL Plus performed the best by far, it contains EPA-regulated components regarding discharge, which limits its application in the United States and other

areas. Even when the performance of Coastalube increases at the highest concentration, it does not measure up to the premium HDL Plus lubricant. This gap in performance is common since many of the components that make up high-quality lubricants are hazardous. The *Spirulina* powder reduced the coefficient of friction by 54%, 70%, and 91% at each increasing concentration. These values outperformed the diesel and Coastalube, except for Coastalube at three (3) percent by volume. This means that the *Spirulina* powder can compete with the commercially available Coastalube lubricant while giving additional rheological and fluid loss benefits that the Coastalube lubricant cannot provide. A comparison of lubricity improvement from this study with values from the literature is shown in Table 6. This combined with its low cost make the *Spirulina* powder a very attractive choice as an additive. Additionally, the performance of the *Spirulina*–Coastalube mix was not significantly different from that of the *Spirulina* alone. This would provide another option for situations in which a higher viscosity or solids content could cause other issues. The user still gains lubricity performance and some of the cost benefit while mitigating potential hydraulic issues.

Table 6. Comparison of % change in the coefficient of friction in this study with values from the literature.

Lubricant Type	Source	Concentration (vol.%)			
		<1%	**1%**	**2%**	**3%**
Diesel	-	-	−2%	−3%	−5%
HDL Plus	-	-	−24%	−75%	−84%
Coastalube	-	-	−2%	−14%	−56%
Spirulina and Coastalube	-	-	−19%	−24%	−28%
Spirulina	-	-	−18%	−23%	−30%
Nanosilica nanoparticles	[28]	−15%	-	-	-
Carbon nanotubes	[28]	−22%	-	-	-
Enhanced activated sludge	[29]	-	-	−38%	-
Raw activated sludge	[29]	-	-	−31%	-
Graphene/triolein complex	[30]	-	−41.4%	-	−60%
SMJH-1	[31]	-	−91.4%	-	-
F-1	[32]	−88%	-	-	-
Polyethylene glycol	[33]	−44.5%	-	-	-
Graphene oxide	[34]	−12.5%	-	-	-

4. Conclusions

This work presents the first comparative study evaluating the performance of *Spirulina* biomass as a potential waste-derived drilling fluid additive to enhance lubricity. Although the premium lubricant outperformed the *Spirulina* powder, it contains EPA-regulated components regarding discharge [35] and, therefore, is not a direct competitor as an environmentally benign dischargeable drilling fluid component. The results showed that similar lubricity performance could be achieved with the *Spirulina* and Coastalube mixed and the *Spirulina* alone. The mix can obtain the benefits of the *Spirulina* while only using half as much of the Coastalube product, which has the potential to substantially reduce operating costs. The other benefit of using the mix of the two is that the viscosity increase is severely scaled back from that of the *Spirulina* alone. This is desirable since the higher concentrations of *Spirulina* alone increased the viscosity of the fluid well beyond what was necessary. Overall, the *Spirulina* powder has a long list of drivers for using it as a lubricating additive or rheological modifier in drilling fluid formulations. The next steps for the course of this research are to study the stability and lubrication properties at higher temperatures, identify the lubricating mechanism (s) of the *Spirulina* biomass, and study the

biodegradability of the *Spirulina*-based drilling fluids. This technology may be particularly valuable for use where there may be discharge to environmentally sensitive areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/lubricants13040149/s1, Table S1: *p*-Values of various properties vs. the independent variables of the different lubricants' concentrations.

Author Contributions: G.M.T.: conceptualization, methodology, investigation, writing—original draft, writing—review and editing. N.A.B.: investigation, writing—original draft, writing—review and editing. W.M.C.: conceptualization, writing—review and editing, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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