

# Phosphorus Fertilizer Effects on Near-Surface Soil Aggregation in Furrow-Irrigated Rice on a Silt-Loam Soil

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## Abstract

Well-aggregated soil has been shown to improve soil infiltration and reduce runoff and soil erosion, making well-aggregated soil important for productive, sustainable agriculture. One factor that may influence near-surface soil aggregate stability is fertilizer application. Rapid dissolution of fertilizers, which are mostly salts, can potentially disperse clays and destabilize aggregates. The objective of this study was to evaluate the potential effect of various fertilizer-phosphorus (P) and -nitrogen (N) sources [*i.e.*, triple superphosphate (TSP), monoammonium phosphate (MAP), chemically precipitated struvite (CPST), electrochemically precipitated struvite (ECST), environmentally smart nitrogen (ESN)] and soil depth on water-stable aggregates (WSA) in furrow-irrigated rice on a silt-loam soil (Typic Albaqualf). Total WSA (TWSA) concentration was unaffected ( $P > 0.05$ ) by fertilizer treatment or soil depth, while WSA concentration was numerically largest ( $P < 0.05$ ) from TSP in the 0 - 5 cm depth ( $0.09 \text{ g}\cdot\text{g}^{-1}$ ), which did not differ from CPST, ECST, and ESN in the 0 - 5 cm depth or the unamended control in the 0 - 5 and 5 - 10 cm depths, and was at least 1.7 times larger than ESN in the 5 - 10 cm depth ( $0.03 \text{ g}\cdot\text{g}^{-1}$ ). Results indicated that WSA concentration among non-struvite fertilizer-P sources was generally similar to that from the struvite fertilizer materials. Principal component analysis determined that 32% of the variation of TWSA was mainly explained by changes in soil bulk density, pH, and electrical conductivity. Long-term, continual annual application of fertilizer-P and N could negatively impact soil aggregate stability, soil structure, and potentially erosion.

## Keywords

Arkansas, Rice Production, Salt Index, Soil Aggregate Stability, Soil Structure, Struvite

## 1. Introduction

Sediment is a major pollutant in surface waters, often originating from erosion from cultivated agricultural fields. In addition to suspended sediment itself, sediment often transports adsorbed nutrients, such as phosphorus (P), and other potential pollutants, such as adsorbed organic pesticide compounds [1]. In mid-2000s, the United States (US) Environmental Protection Agency (EPA) reported that ~15% of US rivers and streams contained excess sediment and >40% of US rivers and streams were polluted by excess nutrients (*i.e.*, nitrogen (N) and P) [1]. By 2013-2014, 22%, 58%, 43% of river and stream lengths surveyed in the US were categorized as poor quality due to excess streambed sediment and excess P and N, respectively [2]. Excess nutrients in surface waters are problematic because they can cause algal blooms, which leads to rapid decomposition and decreased dissolved oxygen, potentially leading to fish kills and aquatic plant suffocation [3]. Excess sediment can also alter habitats, landscapes, and increase turbidity, leading to decreased light penetration, which can inhibit the ability of aquatic organisms to photosynthesize [3].

Soil erosion in cultivated agroecosystems occurs mainly because of raindrop splash, which results from the vertical force of a raindrop converting into lateral shear, displacing soil on the surface, and slaking, which is the degradation of a relatively dry soil aggregate upon complete submersion and subsequent wetting causing entrapped air to pressurize and eventually escape by bursting the aggregate [4] [5]. Collectively, raindrop splash and slaking contribute to detachment, transport, and eventual deposition, which are the primary processes of soil erosion [5].

Particularly in cultivated agroecosystems, maintaining soil structure and soil aggregation facilitates upland erosion control. Soil aggregates form from a combination of physical, chemical, and biological processes and impact agriculture by influencing overall soil health. An increase in abundance and strength of soil aggregates (*i.e.*, aggregate stability) promotes water infiltration and percolation, pore-size distribution, soil water storage, total porosity, and influences rainfall partitioning between infiltration and runoff and decreases erosion [6]. Increased soil aggregation is desirable for productive, sustainable agriculture [3]. Aggregate stability has also been shown to directly influence soil susceptibility to runoff and erosion, where Barthès & Roose [7] linked aggregate resistance and slaking to various soil textures' susceptibility to erosion, showing specifically that soils with greater resistance to slaking were less susceptible to erosion and runoff.

Soil structure, specifically soil aggregate formation and stability, is affected by soil texture, cation exchange capacity (CEC), soil organic matter (SOM), and pH [8]. Soil textures with more clay generally have increased flocculation, thus increased aggregate formation [5]. Similar to clay, SOM also has binding properties, where SOM can coat silt and sand particles, and organic polymers that form from decomposing SOM that can chemically interact with clays and other soil

particles, which further enhances ped formation [5]. Furthermore, an increase in CEC can enhance flocculation due to electrochemical interactions with clay particles, and soils with a low pH often contain larger concentrations of precipitated iron and aluminum oxides, which can also enhance aggregate formation and stability by binding soil particles together [5].

However, two additional factors that can affect aggregate formation, thus aggregate stability, are soil sodium concentration and/or salinity in general. A relatively large sodium concentration can cause clay dispersion and destabilize soil aggregates [9] [10]. Clay particles dispersed by elevated sodium can clog inter-aggregate pores, which, in turn, can reduce surface and sub-surface soil hydraulic conductivity and internal drainage and potentially increase surface runoff and erosion [5]. A widely accepted indicator for potential soil-aggregate dispersion is exchangeable sodium percentage (ESP), where typically an  $ESP \geq 15\%$  is considered the threshold for initiating soil dispersion in clayey soils with generally low initial hydraulic conductivity [9]. However, Crescimanno *et al.* [11] reported soil degradation occurred at ESPs as low as 2% to 5% in soils with low CECs. While soil dispersion is typically caused by sodium, resulting in decreased structure and aggregation and reduced hydraulic conductivity and internal drainage, the rapid dissolution of certain fertilizers can disperse soil and weaken soil-aggregate strength through the effects of elevated salinity [5].

One indicator relating to potential soil salinity that describes fertilizer dissolution properties is the salt index (SI), originally addressed by Rader *et al.* [12]. The SI is a fertilizer dissolution classification system capable of predicting which fertilizers could injure crops by creating a large concentration of fertilizer salts outside the root zone, thus drawing water from the plant to cause dehydration by altering the hydraulic gradient [13]. The SI is scaled relative to 100, which is the assigned SI value for the reference sodium nitrate and is defined as the ratio of the osmotic potential created by a dissolved fertilizer compared to the osmotic potential produced by an equivalent amount of sodium nitrate [12]. It should be noted that Rader *et al.* [12] focused on P fertilizers, where other studies have also evaluated SI of P fertilizers [14]. Latifian *et al.* [14] calculated a SI value of 1.3 for struvite (synthesized from real wastewater and a SI value of 54.3 for a commercial, mixed, N-P-K fertilizer, with a grade of 12-5-14), and determined that struvite's low SI indicated a low risk of struvite dissolution injuring plant roots. **Table 1** summarizes the solubility and SI for various common, commercially available fertilizer-P sources.

The role of P in soil aggregate stability has not been studied in soils characterized by initial acidic conditions, as is commonly present in Arkansas [15] [16]. The addition of P in agricultural soils has been positively associated with reduced soil surface crust formation [17], as the added P contributes to soil aggregate formation. In calcareous soils, P-containing compounds, commonly in the form of phosphoric acid ( $H_3PO_4$ ), have been used as aggregate stabilizers due to the ability to dissolve free calcium carbonate ( $CaCO_3$ ) and form calcium phos-

phate or calcium sulfate compounds that can act as cementing agents for soil aggregates [15]. In acidic soils, the P supplied by P-fertilizers can react with iron (Fe) and aluminum (Al) to form compounds that could potentially behave as soil aggregate stabilizers, which, in turn, can enhance overall soil stability [15].

With struvite's relatively low SI, it stands to reason that struvite has the potential to have a less negative effect on soil aggregation compared to other common, commercially available fertilizer-P sources (**Table 1**). The objectives of this study were: i) to evaluate the potential effect of various fertilizer-P and -N sources [*i.e.*, triple superphosphate (TSP), monoammonium phosphate (MAP), chemically precipitated struvite (CPST), electrochemically precipitated struvite (ECST), and environmentally smart nitrogen (ESN)] on near-surface aggregate stability in furrow-irrigated rice (*Oryza sativa*), and ii) to formulate a predictive model of total water-stable aggregate (TWSA) in the 10 cm depth using soil physical and chemical properties associated with the different fertilizer-P treatments. It was hypothesized that non-struvite-P fertilizers (*i.e.*, TSP, MAP, and ESN) will have a more negative effect on near-surface soil aggregate stability than struvite because of the greater SI and soil-dispersing effects. It was also hypothesized that SOM, bulk density, pH, and electrical conductivity (EC) will represent the main soil properties explaining TWSA variation.

## 2. Materials and Methods

### 2.1. Site Description

Similar to Della Lunga *et al.* [22] field research for this study was conducted in

**Table 1.** Summary of salt index and water solubilities for various fertilizer sources according to salt index values from A & L Laboratories [18] and Latifian *et al.* [14] and solubility values from Chien *et al.* [19], Johnston & Richards [20], and Rech *et al.* [21].

Fertilizer treatment	Salt index	Water solubility range (%)	References
Triple superphosphate	10.1	84 - 95	A & L Canada Laboratories [18] Chien <i>et al.</i> [19] Johnston & Richards [20]
Monoammonium phosphate	26.7	85 - 90	A & L Canada Laboratories [18] Chien <i>et al.</i> [19]
Diammonium phosphate	29.2	85 - 90	A & L Canada Laboratories [18] Chien <i>et al.</i> [19]
Struvite (synthetic wastewater)	0.59	2 - 3.8	Latifian <i>et al.</i> [14] Rech <i>et al.</i> [21]
Struvite (real wastewater)	1.29	2 - 3.8	Latifian <i>et al.</i> [14] Rech <i>et al.</i> [21]

2022 in Arkansas County near Stuttgart, AR at the Rice Research and Extension Center (RREC) (34.46N, 91.46W). The specific study area was 54-m long and 20-m wide and was part of a production scale (16.2 ha), furrow-irrigated rice field [22]. DeWitt silt loam (fine, smectic, thermic Typic Albaqualf) was mapped throughout the study area [23]. The study area consisted of 12 raised beds, 15-cm tall and 30-cm wide, separated by ~46-cm wide furrows and had a mean south-north oriented slope of 2% [23] [24]. The study area has been under cultivated agriculture for at least 15 years. The 30-yr (1991-2020) mean annual precipitation in the region is 128.8 cm [25] and the 30-yr average annual air temperature is 17.3°C [26].

## 2.2. Experimental Design, Treatments, and Plot Layout

The study was a full-factorial, randomized complete block (RCB) design with three replicate blocks across 12 raised beds at the up-slope end of the production-scale field end. The first block was 15 m into the field from the up-slope edge (*i.e.*, crown) of the field, while the second block was 15 m further into the field from the first block and the third block was 15 m further into the field from the second block.

Each block consisted of one randomized replication of each of six fertilizer-P and -N treatments, including ECST, CPST, TSP, DAP, ESN, and unamended control (UC). The ECST material was synthesized by electrochemical precipitation, which consisted of applying an electrical current to a solution of known P and N concentrations through a sacrificial Mg anode that partially decayed and released Mg into solution [27]. The CPST material was created by chemical precipitation within a municipal wastewater treatment plant (WWTP) near Atlanta, GA, where Mg salts were added to the raw wastewater stream to facilitate struvite formation and precipitation that was subsequently pelletized and collected for sale [28]. Environmentally smart nitrogen is urea (44% N) coated with a flexible polymer coating that allows for N release on the basis of soil temperature increase [29]. Each plot within a block was 3-m long by 0.8-m wide (*i.e.*, 2.4 m<sup>2</sup>) from furrow middle to furrow middle, thus there were 18 total plots among the three blocks. The first rice row in a block did not have a raised bed in between adjacent plots, while the other plots in a block had one raised bed in between adjacent fertilizer-P-treatments plots.

## 2.3. Field Management

On 14 September 2021, crop residue left in the field from the harvested 2021 rice crop was burned. On 22 October 2021, a mix of 50% annual rye (*Lolium multiflorum*), 25% Australian winter peas (*Pisum sativum subsp. arvense*), 12.5% crimson clover (*Trifolium incarnatum*), and 12.5% radish (*Raphanus sativus*) was planted at a rate of 28.02 kg seed·ha<sup>-1</sup> as a cover crop throughout the entire production-scale field. On 29 April 2022, the study area was drill-seeded with the rice cultivar FP7521 (RiceTec, Alvin, TX) at 23.5 kg seed·ha<sup>-1</sup> to achieve

~217,321 seeds·ha<sup>-1</sup>.

Throughout the 2022 rice growing season, the entire production-scale field was furrow-irrigated on a weekly basis with water from a nearby surface reservoir initially and then with re-circulated water from the down-slope end of the field as the growing season progressed. In addition, throughout the 2022 rice growing season, herbicides were applied as-needed according to University of Arkansas, Cooperative Extension Service recommendations for furrow-irrigated rice production [30].

The first of four fertilizer applications occurred on 13 May, 2022, where P, N, and Zn were manually broadcast to their respective plots. Except for the UC, each plot received the equivalent rate of 14.7 kg P·ha<sup>-1</sup> from each fertilizer-P source (*i.e.*, DAP, TSP, ECST, and CPST) and, because ESN contains no P, 14.7 kg P·ha<sup>-1</sup> as DAP was applied to the ESN plots to balance the fertilizer-P amount among all other fertilizer-P treatments. Furthermore, on May 13, all treatments that did not receive DAP (*i.e.*, TSP, ECST, CPST, and UC) received an initial N application, as urea (46% N), in different amounts to balance the applied-N with the amount of N provided by DAP (14.5 kg N·ha<sup>-1</sup>). Additionally, 11.2 kg Zn·ha<sup>-1</sup> as ZnSO<sub>4</sub> were manually surface-applied to all treatments and, based on initial soil property analyses that indicated soil-test-K concentrations were already at optimal levels, no K was added. On 2 June, 2022, 140 kg N·ha<sup>-1</sup> as ESN (44% N) were applied to the ESN treatment plots. All ESN that would be used for the entire growing season was applied at once because of ESN's reported slow-release properties [29]. All other plots received 37.0 kg N·ha<sup>-1</sup> as urea and, based on recommendations from Hardke [30], two 51.6 kg N·ha<sup>-1</sup> applications as urea were made to all treatment plots, except for ESN, on 9 June and 16 June, 2022.

#### 2.4. Soil Sample Collection

Soil samples for initial soil property characterization were collected from the top 10 cm of the raised beds using a 2-cm diameter push probe on 24 March, 2022, where one core from each plot per block was collected and combined for one composite sample per block (*i.e.*, 3 total soil samples). On 6 May, a set of soil samples was collected on a plot-by-plot basis with a 4.8-cm-diameter, stainless steel core chamber and slide hammer for beginning-of-season BD determinations. On 27 August, 2022, an additional two sets of soil samples were collected following the same procedures as indicated above for end-of-season determination of soil physical and chemical properties and BD. All samples were oven-dried at 70°C for 48 hours, ground, sieved through a 2-mm mesh screen, and analyzed for sand, silt, and clay content (initial samples only), pH and electrical conductivity (EC), and SOM, total carbon (TC) and nitrogen (TN), and extractable nutrient concentrations (P, K, Ca, Mg, S, Na, Fe, Mn, and Zn). Soil particle-size analyses were conducted using a modified, 12-hour hydrometer method [31]. Soil pH and EC were analyzed potentiometrically in a 1:2 soil mass:water sus-

pension [32]. Soil OM was measured by loss-on-ignition [33]. Total C and TN were measured by high-temperature combustion on a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ) [34]. Soil nutrients were extracted with Mehlich-3 extracting solution in 1:10 soil mass:extractant volume ratio and analyzed by inductively coupled, argon-plasma spectrometry (Spectro Arcos ICP, Spectro Analytical Instruments, Inc., Wilmington, MA) [35]. Measured concentrations ( $\text{g}\cdot\text{kg}^{-1}$  or %) for extractable nutrients, TN, TC, and SOM were converted to contents ( $\text{kg}\cdot\text{ha}^{-1}$ ) using the measured bulk density and 10-cm sample depth interval on a plot-by-plot basis, where contents were subsequently used for statistical analyses.

Soil sample collection for aggregate stability analyses occurred on 27 August, 2022 from the top 10 cm using a slide hammer with a 7.3-cm-diameter, stainless steel core chamber [8] [36]. Two soil cores were collected in association with each plot, one from on top of the bed inside the plot area and the second from the top of the bed in a non-fertilized area outside the plot, but within 2 m of the inside-plot sample. Both cores were separated into the 0 - 5- and 5 - 10-cm intervals and placed in separate plastic bags for transport.

## 2.5. Aggregate Stability

Similar to recent procedures used by Arel *et al.* [8] for silt-loam soils in the Lower Mississippi River Valley, aggregate stability samples were gently, manually broken apart, gently pushed through a 6-mm mesh screen, and laid out to dry in a greenhouse for seven days at 31°C. After drying, 150 g ( $\pm 0.1$  g) of air-dry soil from a single aggregate stability soil sample were placed into the top of a nest of five sieves in a wet-sieve apparatus [37]. The nest of sieves was arranged in decreasing order from top to bottom: 4-, 2-, 1-, 0.5-, and 0.25-mm. The sieve nest was attached to an arm that mechanically oscillated the sieve nest containing the soil sample in an ~120-cm tall by 40-cm diameter column of tap water at 30 oscillations per minute for five minutes. After the mechanically imposed disturbance to the soil samples, the nest was manually removed from the wet-sieve apparatus. The soil aggregates remaining on top of each sieve were transferred into a pre-weighed, aluminum container for each sieve by gently washing the aggregates with a water bottle and left to settle for about 10 minutes. After settling, the excess water was slowly decanted, ensuring that no sediment or aggregates were discarded, and the five aluminum containers were placed into a forced-draft oven set to 70°C to oven-dry for 24 hours. The three replications of each fertilizer-soil depth-sample location combination were wet-sieved in succession before the soil that passed through the bottom 0.25-mm sieve was removed from the apparatus and the column containing the sediment-suspended water was rinsed and filled with new water to proceed with the three replications from the next treatment combination.

After oven-drying, the soil samples were weighed so that WSA concentration by size class (*i.e.*, >4-, 2- to 4-, 1- to 2-, 0.5- to 1-, and 0.25- to 0.5-mm sizes)



could be calculated. Before calculating WSA concentrations, coarse fragments (*i.e.*, small pebbles from the alluvial soil parent material) were removed from the two largest size classes (*i.e.*, >4- and 2- to 4-mm sizes) for each sample by sieving through a 2-mm mesh sieve, where the soil aggregates were manually broken up and pushed through the sieve, while the coarse fragments remained intact. Coarse fragments were weighed and the coarse fragment mass was subtracted from the oven-dry soil mass. Water-stable-aggregate concentrations were calculated by dividing the oven-dry mass of aggregates retained on each sieve by the initial air-dried soil mass (*i.e.*, ~150 g) that was corrected to an oven-dry basis. Furthermore, total water-stable aggregates (TWSA) were calculated by summing the soil aggregate mass retained on all five sieves and dividing by the original air-dried soil mass that was corrected to an oven-dry basis.

For individual replicate data for both WSA and TWSA, two datasets were created and analyzed, where one dataset represented the difference in aggregate stability from inside and outside the plot (*i.e.*, In-Out) on a plot-by-plot basis, while the second dataset represented only data from inside the plot (*i.e.*, In). Using the data obtained from the In dataset, a weighted average, on a plot-by-plot basis, between TWSA from the 0- to 5- and 5- to 10-cm depth was used to calculate the TWSA representing the 0- to 10-cm depth, hereafter referred to as TWSA-10.

## 2.6. Statistical Analyses

Based on a RCB, split-split-plot design, a three-factor analysis of variance (ANOVA) using PROC GLIMMIX in SAS (version 9.4, SAS Institute, Inc., Cary, NC) was conducted to evaluate the effects of fertilizer treatment (DAP, TSP, ECST, CPST, ESN, and the UC; whole-plot factor), soil depth (0 - 5 and 5 - 10 cm; split-plot factor), aggregate size class (>4-, 2- to 4-, 1- to 2-, 0.5- to 1-, and 0.25- to 0.5-mm sizes; split-split-plot factor), and their interactions on both WSA datasets (*i.e.*, In-Out and In). Based on a RCB, split-plot design, a two-way ANOVA was conducted to evaluate the effects of fertilizer treatment (whole-plot factor), soil depth (split-plot factor), and their interaction on TWSA for both datasets (*i.e.*, In-Out and In). All parameters from the In-Out dataset were analyzed using a normal distribution, while all the parameters from the In dataset were analyzed using a gamma distribution, significance was judged at  $P < 0.05$ , and, when appropriate, treatment means were separated by least significant difference at the 0.05. Studentized residuals were plotted to evaluate the potential presence of outliers and the degree of homoscedasticity. As a result, no value was removed from the dataset and the variance among treatments was considered homogeneous.

A multiple regression analysis was conducted in JMP (version 17.0, SAS Institute, Inc., Cary, NC) to determine the degree of multicollinearity among soil physical and chemical properties with TWSA-10 from the In dataset as the response variable. Based on the results of the multiple regression, a principal



component analysis (PCA) was conducted in JMP using the difference in soil physical and chemical properties (*i.e.*, contents for all nutrients and/or compounds) calculated as end minus the beginning of the season to determine the dominant contributing factors to assess the variance of TWSA-10 as percentage across the study area. A stepwise backwards regression was used on the principal components with an Eigenvalue greater than 1 to determine the set of best-fitting models. The Bayesian information criterion (BIC) was used as the stopping rule to evaluate the maximum likelihood of all models. All variables in the PCA were assumed to have a continuous, normal distribution. Significance for the PCA was also determined at the 0.05 level.

### 3. Results and Discussion

#### 3.1. Initial Soil Properties

Initial soil properties in the top 10 cm were as uniform as could be expected throughout the study area (**Table 2**). Despite minor variations in sand, silt, and clay concentrations, the soil texture among all samples was silt loam (**Table 2**). Soil pH averaged 5.3 in the top 10 cm, which was lower than the ideal soil pH (6.0 - 6.5) for rice production because P is more easily immobilized by iron and aluminum compounds below pH 6 [38]. Extractable-soil P, K, Ca, Mg, S, Na, Fe, Mn, and Zn, and BD averaged 25, 142, 656, 112, 17.5, 67.2, 383, 158, and 17.6 mg·kg<sup>-1</sup>, and 1.22 g·cm<sup>-3</sup>, respectively, in the top 10 cm throughout the study area (**Table 2**). All extractable soil nutrients reported were above optimum levels for row-crop growth [39]. In addition, SOM averaged 2.5%, total C averaged 1.1%, and total N averaged 0.1% in the top 10 cm (**Table 2**). Based on measured initial soil properties throughout the study area, all agronomically relevant soil properties, with the exception of soil pH, were at a level that was considered adequate for optimal rice growth [16]. The measured BD variation within the study area contributed to the wide range in measured soil property contents (**Table 2**).

#### 3.2. Water-Stable-Aggregate Concentrations

To evaluate the potential impact of fertilizer treatment on WSA, the In-Out WSA data set was first assessed. Results showed that neither fertilizer treatment, soil depth, nor aggregate-size class affected the difference in WSA concentrations between the fertilized (In) and unfertilized plots (Out; **Table 3**). The absence of significant differences most likely was due to the combination of the dataset including only one growing season and that the study area has been under cultivation for at least the last 15 years. Throughout the last 15 years of cultivation, nutrients increased to the point where no nutrient deficiencies existed that needed correction, as the initial soil properties showed nutrient concentrations close to or above optimum levels for rice production on a silt-loam soil (**Table 2**). Consequently, the In only WSA dataset was evaluated.

Based on the In only dataset, WSA concentration differed between soil depths

**Table 2.** Summary of initial soil physical and chemical property means (n = 5) and standard errors (SE) for the soil used in the current study.

Soil property	Mean ( $\pm$ SE)
BD (g·cm <sup>-3</sup> )	1.22 (<0.1)
Sand (%)	15.8 (0.3)
Silt (%)	72.2 (0.3)
Clay (%)	12.0 (0.2)
Electrical conductivity (dS·m <sup>-1</sup> )	0.16 (<0.1)
pH	5.33 (0.1)
Extractable nutrients (mg·kg <sup>-1</sup> )	
P	25.0 (0.7)
K	142 (7.7)
Ca	656 (8.7)
Mg	112 (2.5)
S	17.5 (1.0)
Na	67.2 (2.9)
Fe	383 (20.2)
Mn	158 (15.2)
Zn	17.6 (0.7)
Soil organic matter (%)	2.5 (<0.1)
Total C (%)	1.1 (<0.1)
Total N (%)	0.1 (<0.1)
Extractable nutrients (kg·ha <sup>-1</sup> )	
P	30.5 (0.2)
K	174 (1.3)
Ca	803 (6.2)
Mg	137 (1.1)
S	21.4 (0.2)
Na	82.3 (0.6)
Fe	468 (3.6)
Mn	193 (1.5)
Zn	21.6 (0.2)
Soil organic matter (kg·ha <sup>-1</sup> )	30116 (231)
Total C (kg·ha <sup>-1</sup> )	13385 (103)
Total N (kg·ha <sup>-1</sup> )	1236 (95)

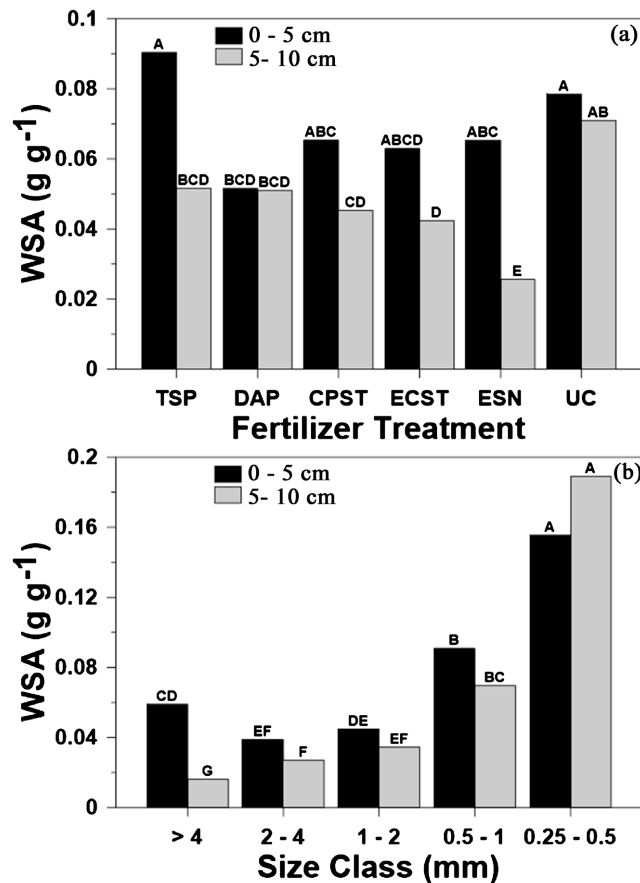
**Table 3.** Summary of the effects of fertilizer, soil depth, aggregate size class, and their interactions on water-stable aggregate (WSA) and total WSA (TWSA) concentrations from the In-Out and In only datasets.

Source of variation	WSA		TWSA	
	In - Out	In	In - Out	In
	<i>P</i>			
Fertilizer	0.47	<0.01	0.47	0.18
Depth	0.15	<0.01	0.22	0.16
Fertilizer × depth	0.32	0.02	0.50	0.77
Size class	0.08	<0.01	-	-
Fertilizer × size class	0.73	0.41	-	-
Depth × size class	0.31	<0.01	-	-
Fertilizer × depth × size class	0.33	0.07	-	-

within fertilizer treatments ( $P = 0.02$ ) and differed between soil depths within aggregate size classes ( $P < 0.01$ ; **Table 3**). Averaged across aggregate-size class, WSA concentration was numerically largest from TSP in the 0 - 5 cm depth, which did not differ from CPST, ECST, and ESN in the 0 - 5 cm depth or the UC in the 0 - 5 and 5 - 10 cm depths and was at least 1.7 times larger than ESN in the 5 - 10 cm depth, which was smallest (**Figure 1(a)**). It is possible that the carrier cation to  $\text{PO}_4^-$  in TSP (*i.e.*,  $\text{Ca}^{+2}$ ) contributed to the promotion of flocculation and structure formation, which has been shown to occur with divalent cations [5]. Water-stable-aggregate concentration from ECST in the 5 - 10 cm depth was similar to that from ECST in the 0 - 5 cm depth, DAP in the 0 - 5- and 5 - 10 cm depths, and TSP and CPST in the 5 - 10 cm depths (**Figure 1(a)**). In addition, WSA concentration did not differ between soil depths from DAP, CPST, ECST, and the UC, while WSA concentration was larger in the 0 - 5 than in the 5 - 10 cm depth for TSP and ESN. Furthermore, WSA concentration was similar between soil depths for CPST and ECST and did not differ in the 0 - 5 and 5 - 10 cm depths from CPST and ECST, but WSA concentration was 1.5 times greater from CPST in the 0 - 5 than from ECST in the 5 - 10 cm depth (**Figure 1(a)**). It is possible that the cover crops and crop residue burning used for field management elevated SOM, OC, and/or divalent cation concentrations in the upper 5 cm of the soil, all of which could increase WSA concentration, and may explain WSA concentration differences by soil depth between the struvite fertilizers, TSP, and ESN [3]. It is plausible that the combined effects of the cover crop and residue burning also affected WSA concentrations in the DAP and UC treatments, but the variability associated with WSA concentrations between depths in the DAP and UC treatments masked a potential significant difference in WSA concentration between soil depths. Across the two soil depths, the DAP and ESN treatments, which were the only two treatments that did not receive any urea-N

additions, behaved differently (**Figure 1(a)**). The DAP and ESN treatments were characterized by the same fertilizer-P source, amount, and timing of application, differing only in the fertilizer-N source and number of applications. As suggested by Sithole *et al.* [40] in a long-term study aimed to evaluate aggregate stability under different tillage and fertilizer-N treatments, the all-upfront fertilizer-N application in the ESN treatment, coupled with the low water solubility of ESN compared to urea, most likely allowed deeper N penetration into the soil and a synergistic effect with P that reduced soil aggregation (**Figure 1(a)**).

Averaged across fertilizer treatment, WSA concentration was numerically largest in the 0.25 - 0.5 mm size class in the 5 - 10 cm depth, which did not differ from that in the 0.25 - 0.5 mm size class in the 0 - 5 cm depth and was at least 1.6 times greater than WSA in all other size class-soil depth combinations (**Figure 1(b)**). Multiple studies have reported that, in agricultural settings, WSA concentration was greatest in the 0.25 - 0.5 mm size class [8] [36] [41] [42] [43]. Water-stable-aggregate concentration was numerically smallest from the > 4-mm



**Figure 1.** Analysis of variance summary of the effects of fertilizer treatment [*i.e.*, triple superphosphate (TSP), diammonium phosphate (DAP), chemically precipitated struvite (CPST), electrochemically precipitated struvite (ECST), environmentally smart nitrogen (ESN), and unamended control (UC)] and soil depth (a) and aggregate-size class and soil depth (b) on WSA concentration. Different letters atop bars in a panel indicate means are different at  $P < 0.05$ .

size class in the 5 - 10 cm depth (**Figure 1(b)**), which was similar to results reported in Anders *et al.* [41] and Motschenbacher *et al.* [42] in flood-irrigated rice in east-central Arkansas and Arel *et al.* [8] across multiple silt-loam soils with and without cover crops in the Lower Mississippi River Valley, mainly in eastern Arkansas. Water-stable-aggregate concentration in the 0.5 - 1-mm size class in the 0 - 5 cm depth was similar to that in the 0.5 - 1 mm size class in the 5 - 10 cm depth, and WSA concentration in the >4-mm size class in the 0 - 5 cm depth was similar to that in the 0.5 - 1-mm size class in the 5 - 10 cm depth and in the 1 - 2-mm size class in the 0 - 5 cm depth (**Figure 1(b)**). Water-stable-aggregate concentration in the 2 - 4 mm size class in the 0 - 5 cm depth was similar to that in the 2 - 4 mm size class in the 5 - 10 cm depth and in the 1 - 2 mm size class in the 5 - 10 cm depth (**Figure 1(b)**). Furthermore, WSA concentration did not differ between soil depths in the 2 - 4-, 1 - 2-, 0.5 - 1-, and 0.25 - 0.5-mm size classes, while WSA concentration was 3.6 times larger in the 0 - 5 than in the 5 - 10 cm depth in the >4-mm size class (**Figure 1(b)**).

The generally increasing WSA concentration with decreasing size class is potentially due to increased organic matter concentration among the smaller size [41] [42]. Soil organic matter constituents, such as plant roots, polysaccharides, or microbial cells, can coat and enmesh mineral particles, allowing particles to cohere and form aggregates [3]. Thus, as SOM and/or SOC increase, soil aggregate concentration also tends to increase [3]. Furthermore, Motschenbacher *et al.* [42] reported that soil C and N content in a silt-loam soil under conventional tillage was greatest in the 0.25 - 0.5-mm size class in the 0 - 5 and 5 - 10 cm depths. Aggregate decomposition is typically enhanced by tillage, and larger aggregates are typically most prone to decomposition from mechanical disturbances (*i.e.*, tillage) [41] [44].

Similar to the results of the current study, Anderson *et al.* [36] evaluated land use (*i.e.*, deciduous and coniferous forest, native prairie, managed grassland, row-crop agriculture) and tillage effects (*i.e.*, conventional- and no tillage in a rice-soybean crop rotation) on soil aggregate stability in alluvial and loessial soils with soil-loam surface textures in the Arkansas Delta region of the Lower Mississippi River Valley. Results showed that WSA concentration was largest in the 0.25 - 0.5-mm size class under conventional tillage, but, in contrast to the current study, WSA concentration was numerically smallest in the 1 - 2-mm size class [36].

Although, to date, no known studies have evaluated aggregate stability in a furrow-irrigated rice system, similarities and differences to results reported in this study have been previously documented for flood-irrigated rice on similar soils in eastern Arkansas [41] [42]. In a field study of rice-based crop rotations with soybean (*Glycine max*), corn (*Zea mays*), and winter wheat (*Triticum aestivum*) on a silt-loam soil in east-central Arkansas, Anders *et al.* [41] evaluated the effects of conventional tillage and no tillage on WSA concentration and soil aggregate C and N contents. Similar to the results of the present study, Anders *et*

*al.* [41] reported that WSA concentration and soil aggregate C content in a conventionally tilled soil were typically largest from the 0.25 - 0.5-mm size class. Furthermore, Motschenbacher *et al.* [42] followed up the Anders *et al.* [41] study by evaluating the effects of rice-based crop rotations with soybean, corn, and winter wheat, tillage (*i.e.*, no-tillage and conventional tillage), and soil depth (*i.e.*, 0 - 5 and 5 - 10 cm) after 10 years of consistent management on WSA-, C-, and N concentrations among WSA size classes in the same Dewitt silt-loam soil as evaluated in the present study. Similar to results of the present study, Motschenbacher *et al.* [42] reported that WSA concentration was generally largest from the 0.25 - 0.5-mm size class in both the 0 - 5 and 5 - 10 cm depths, and that WSA concentration was generally smallest from the >4-mm size class. In addition, WSA C content was largest from the 0.25 - 0.5 mm size class in both the 0 - 5 and 5 - 10 cm depths [42].

### 3.3. Total Water-Stable-Aggregate Concentrations

Summing across size classes, TWSA concentration was calculated and evaluated. However, in contrast to WSA among size classes, TWSA was unaffected ( $P > 0.05$ ) by fertilizer treatment or soil depth when the In-Out and In only data sets were evaluated (Table 3). Consequently, TWSA concentration ranged from 0.33 g·g<sup>-1</sup> in DAP to 0.53 g·g<sup>-1</sup> in TSP and averaged 0.41 g·g<sup>-1</sup> across all fertilizer treatments in the 0 - 5-cm depth interval. Motschenbacher *et al.* [42] reported that TWSA concentration in the continuous rice rotation in the 0 - 5 cm was approximately 0.03 g·g<sup>-1</sup>. Anders *et al.* [41] reported that TWSA concentration in the continuous rice rotation from conventional tillage was approximately 0.07 g·g<sup>-1</sup> in the 0 - 5 and 5 - 10 cm depths. Total WSA concentration ranged from 0.24 g·g<sup>-1</sup> in ESN to 0.49 g·g<sup>-1</sup> in TSP and averaged 0.35 g·g<sup>-1</sup> across all fertilizer treatments in the 5 - 10-cm depth interval. Motschenbacher *et al.* [42] reported that TWSA concentration in the continuous rice rotation in the 5 - 10 cm depth was approximately 0.05 g·g<sup>-1</sup>. It is possible that the TWSA concentrations reported in Motschenbacher *et al.* [42] and Anders *et al.* [41] were considerably lower than TWSA concentrations reported in the current study because initial land-leveling activities that were used uniformly throughout the study area prior to the Motschenbacher *et al.* [42] and Anders *et al.* [41] studies likely severely disrupted initial macroaggregation, thus reducing TWSA concentrations.

Similar to the results of the current study, Arel *et al.* [8], who evaluated the effects of cover crops in various silt-loam soils on near-surface soil aggregate stability, reported that, averaged across all no-cover-crop treatments and both depths (*i.e.*, 0 - 5 and 5 - 10 cm), TWSA concentration was 0.46 g·g<sup>-1</sup> and that TWSA concentration averaged across all of the cover-crop treatments across both depths was 0.45 g·g<sup>-1</sup>. In addition, a study that evaluated the effects of alternative residue management and irrigation practices in a wheat-soybean double-crop production system on aggregate stability in a silt-loam soil reported that TWSA concentration was generally larger from the 0 - 5 than from the 5 - 10 cm depth

[43]. Similar to Arel *et al.* [8], the lack of a significant fertilizer treatment effect on TWSA could be due to the short duration of the study (*i.e.*, only ~4 months of one growing season), where a significant fertilizer treatment effect may become increasingly apparent over a longer period of time of consistent management (*i.e.*, repeated annual application of the same fertilizer-P sources).

### 3.4. Principal Component Analysis

The multiple regression analysis was performed using the difference (*i.e.*, end minus beginning of the season) in all predictor variables (*i.e.*, BD, pH, EC, P, K, Ca, Mg, S, Na, Fe, Zn, TN, TC, and SOM), resulting in a model that was highly non-significant ( $P = 0.99$ ) and an  $R^2$  of 0.53 (Table 4). Due to the limited number of observation (*i.e.*, 18) and the relatively large number of predictors properties used (*i.e.*, 15), only linear parameters were included in the model without any interaction terms in order to obtain statistically testable results in relation to

**Table 4.** Summary of multiple regression analyses to predict total water-stable aggregate (TWSA) concentration (%;  $n = 18$ ) from the variation in soil properties from the top 10 cm (*i.e.*, end minus beginning of the season) for the 2022 growing season at the Rice Research and Extension Center near Stuttgart, AR.

Response variable	Model parameter <sup>†</sup>	Coefficient (Standard error)	Variance inflation factor	Overall model $P$ -value	Overall model $R^2$	RMSE <sup>†</sup>
TWSA-10	BD ( $\text{g}\cdot\text{cm}^{-3}$ )	-16.2 (397)	21.8	0.99	0.53	21.9
	pH	21.7 (97.3)	21.7			
	EC ( $\text{dS}\cdot\text{m}^{-1}$ )	135.2 (398)	23.2			
	P ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.15 (3.7)	33.8			
	K ( $\text{kg}\cdot\text{ha}^{-1}$ )	-0.16 (0.3)	5.9			
	Ca ( $\text{kg}\cdot\text{ha}^{-1}$ )	-0.04 (0.19)	5.8			
	Mg ( $\text{kg}\cdot\text{ha}^{-1}$ )	-0.61 (1.7)	17.1			
	S ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.31 (1.9)	3.7			
	Na ( $\text{kg}\cdot\text{ha}^{-1}$ )	-0.34 (0.7)	27.6			
	Fe ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.03 (0.6)	35.3			
	Mn ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.01 (0.2)	3.2			
	Zn ( $\text{kg}\cdot\text{ha}^{-1}$ )	-1.36 (2.1)	11.2			
	TN ( $\text{kg}\cdot\text{ha}^{-1}$ )	-0.16 (0.5)	59.6			
	TC ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.01 (0.1)	64.5			
	SOM ( $\text{kg}\cdot\text{ha}^{-1}$ )	0.001 (<0.1)	11.3			
Intercept	22.06	-				

<sup>†</sup>Bulk density (BD); electrical conductivity (EC); total nitrogen (TN); total carbon (TC); soil organic matter (SOM); and root mean square error (RMSE).



the total degree of freedom (*i.e.*, 17). The standard deviation of the prediction errors [*i.e.*, root mean square error (RSME)] of 21.9% was numerically greater than the standard deviation of the response variable TWSA-10 (11.0%), suggesting that the resulting multiple regression model was not able to appropriately capture the variability of the response variable across the study area (**Table 4**) [45]. The relatively low  $R^2$  also indicated that different and/or additional predictors should be considered and included in model to evaluate TWSA in agricultural fields (**Table 4**). Using the threshold of 5, the variance inflation factor (VIF) across all predictors, except for S and Mn content, included in the multiple regression analysis indicated a large degree of multicollinearity (**Table 4**) [46] [47]. Consequently, the interpretation of the predictors' coefficients in the multiple regression analysis was not considered reliable due to the large degree of multicollinearity [46] [47] and necessitated an alternative approach.

A subsequent PCA was performed that took into consideration all measured soil properties in the current study. A PCA was preferred in place of a cluster analysis to better address multicollinearity and to frame results and conclusions on actual measured results and not on deduction or experts' knowledge as commonly occurs with cluster-analysis studies [48]. The PCA was performed on correlations where all the predictors were modeled as continuous variables and the categorical parameter fertilizer-P source (*i.e.*, ECST, CPST, TSP, DAP, ESN, and UC) was added as supplementary information in the model [49]. All predictors in the model, except soil pH, were unaffected ( $P > 0.05$ ) by fertilizer-P source (data not shown), but the inclusion in the PCA as a projected variable (*i.e.*, supplementary information) likely helped enrich the interpretation of the resulting model [49]. The first four principal components were selected, based on their Eigenvalues  $> 1$  and cumulative contribution of 83.7% (**Table 5**), to be used as orthogonal predictors in a second regression analysis [50]. The Bartlett test indicated that the Eigenvalues for the first four principal components differed significantly than zero ( $P < 0.05$ ; **Table 5**). The multiple linear regression backward function with the four principal components and using the BIC as the stopping rule resulted in a model where only the fourth principal component was retained (**Table 6**). The resulting new model was highly significant ( $P = 0.014$ ;  $R^2 = 0.32$ ; RMSE = 9.36; **Table 6**), indicating a substantial improvement in precision compared to the previous multiple linear regression model (**Table 4**).

As hypothesized, variations in TWSA-10 due to the combination of changes in BD, pH, and EC were significant (**Table 6**). As BD increased, the 4<sup>th</sup> principal component decreased and, due to the negative sign in the prediction expression, TWSA-10 increased (**Table 6**). As soil pH and EC increased, TWSA-10 decreased (**Table 6**). Somewhat similar results were reported by Idow [51] from PCA/multiple regression analyses in tropical Alfisols where soil aggregate stability was significantly affected by BD, pH and SOM. However, the interpretation of the relationships between BD, pH, EC, and TWSA-10 in the final model in the current study is limited to the range of measured values from the beginning to

**Table 5.** Summary of principal components analysis with Eigenvalues > 1 and relative contribution.

Principal components	Eigenvalue	% Contribution	Bartlett test <i>P</i> > Chisq
1	5.63	37.5	<0.01
2	2.52	16.8	<0.01
3	2.02	13.5	<0.01
4	1.30	8.7	<0.01
5	1.08	7.2	<0.01

**Table 6.** Summary of stepwise regression with Principal Component 4 on measured soil properties with associated parameter estimates loaded in principal component 4.

Principal component	Model parameter <sup>†</sup>	Components coefficient	Overall model <i>P</i> -value	Overall model R <sup>2</sup>	RMSE <sup>†</sup>
4	BD (g·cm <sup>-3</sup> )	-3.07	0.014	0.32	9.36
	pH	1.26			
	EC (dS·m <sup>-1</sup> )	2.13			
	P (kg·ha <sup>-1</sup> )	0.04			
	K (kg·ha <sup>-1</sup> )	0.01			
	Ca (kg·ha <sup>-1</sup> )	0.01			
	Mg (kg·ha <sup>-1</sup> )	0.03			
	S (kg·ha <sup>-1</sup> )	-0.03			
	Na (kg·ha <sup>-1</sup> )	0.004			
	Fe (kg·ha <sup>-1</sup> )	0.003			
	Mn (kg·ha <sup>-1</sup> )	0.01			
	Zn (kg·ha <sup>-1</sup> )	0.01			
	TN (kg·ha <sup>-1</sup> )	0.003			
	TC (kg·ha <sup>-1</sup> )	-0.0001			
	SOM (kg·ha <sup>-1</sup> )	-0.0001			
	Intercept	-0.53			
Prediction expression		38.41 - 5.45* (Principal 4)			

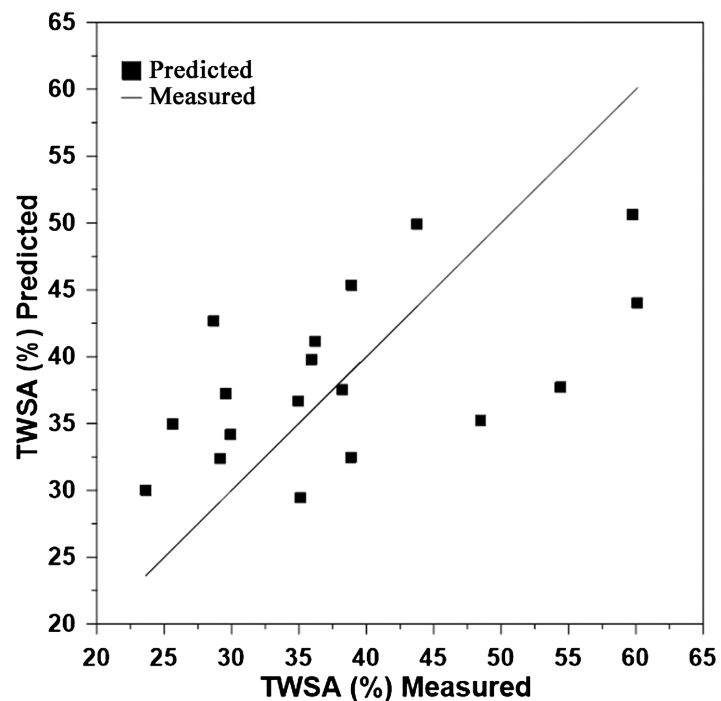
<sup>†</sup>Bulk density (BD); electrical conductivity (EC); total nitrogen (TN); total carbon (TC); soil organic matter (SOM); and root mean square error (RMSE).

the end of the growing season in order to logically explain how the factors varied with each other [51].

Bulk density, pH, and EC ranged from 1.16 to 1.27 g·cm<sup>-3</sup> and from 1.0 to 1.26 g·cm<sup>-3</sup>, from 5.4 to 5.2 and from 5.2 to 6.2, and from 0.14 to 0.17 dS·m<sup>-1</sup> and from 0.13 to 0.34 dS·m<sup>-1</sup> at the beginning and end of the season, respectively. As

BD increases, macro- and microaggregates are physically compressed together favoring aggregate formation that leads to a more stable soil structure, thus increasing aggregate stability [52]. However, this relationship only remains valid until the breaking point of the soil aggregate is achieved or exceeded [52]. Several studies reported a negative correlation between BD and TWSA in general, likely due to measured BD values being close to or above  $1.30 \text{ g}\cdot\text{cm}^{-3}$  [51] [53] [54]. As soil pH increases, hydraulic conductivity and chelation processes decrease, while clay dispersion generally increases, causing aggregate stability to decrease [55]. The dissolution of Al- and Fe-oxides and the reduced formation of humic compounds as pH increases tends to reduce the presence and amount of cementing agents that can enhance soil aggregate stability [55] [56]. Soil EC has been directly correlated to salinity and sodicity levels in the soil [57]. As soil EC increases, regardless of the range within which such EC increase occurs, clay flocculation may decrease, potentially negatively impacting soil aggregate stability [11]. Somewhat similar to what was hypothesized, SOM was significant in the final model of the current study, but with a minor role compared to BD, pH, and EC, likely due to the limited changes in SOM that occurred during the course of the single growing season (Table 6).

Though significant, the final model from PCA obtained in the current study overestimated the predicted values when TWSA was within the range of 20% and 45% and underestimated the predicted values when TWSA was within the range of 45% and 60% (Figure 2). Consequently, predictions outside the measured



**Figure 2.** Graphical representation of measured total water-stable aggregate (TWSA) concentrations and predicted TWSA based on the regression model from Principal Component 4 (Table 6).

TWSA range reported in the current study should be considered as unreliable. Further studies should consider including data from several consecutive growing seasons, changes in soil textural properties, and external, environmental factors, such as soil volumetric water content and climatic conditions, in the modeling analysis of TWSA.

### 3.5. Practical Implications

Aggregate stability is an important aspect of maintaining and improving productive, sustainable agriculture by providing soil erosion control from more impact-resistant aggregates and increasing water infiltration into and percolation through the soil upper soil profile, water storage within the profile, and overall soil health. Improving overall soil health from increased soil aggregation can increase crop establishment, growth, and yield. Despite the benefits of strong and abundant aggregates, aggregate stability can be impacted by a multitude of factors (*i.e.*, fertilizer source, SOM, and field management), and protective measures to maintain aggregate strength (*i.e.*, cover crops and conservation tillage) should be implemented in agricultural environments. Based on the results of this study, it is reasonable to assume that throughout the four-month study, near surface aggregate stability in furrow irrigated rice was not significantly impacted by fertilizer sources used in this study. However, it is likely that longer durations of consistent application of fertilizer sources could reveal a significant fertilizer treatment effect. Thus, further research that evaluates the impact of long-term fertilizer application on near-surface aggregate stability should be conducted to definitively report the relationship between fertilizer-P application and near-surface aggregate stability, so soil aggregate stability can be further preserved.

## 4. Conclusion

This study evaluated the effects of various fertilizer-P and N sources on WSA concentration among five size classes and TWSA concentration in furrow irrigated rice on a silt-loam soil at 0 - 5 and 5 - 10 cm depth intervals. Contrary to the original hypothesis that non-struvite-P fertilizers (*i.e.*, TSP, MAP, and ESN) would have a greater impact on near-surface soil aggregate degradation, WSA concentration among the non-struvite-P fertilizers was similar to struvite fertilizers in all treatments except for WSA concentration from ESN in the 5 - 10 cm depth. Furthermore, fertilizer treatment did not significantly affect size class, whereas size class was significantly affected by depth. While the hypothesis is not directly supported by the results, it is expected that long-term, consistent application of fertilizer-P and N sources could reveal a significant impact of fertilizer treatment on soil-aggregate stability. The PCA showed the potential to predict TWSA concentration using soil properties, specifically BD, EC, and pH, although additional parameters need to be considered in order to improve overall model precision. Based on the results of this study, it can be concluded that in

the short duration of the study, non-struvite-P and N fertilizer sources and struvite sources minimally impacted near-surface soil-aggregate stability.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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