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# Impact of Long-Term Nutrient Supply Options on Soil Aggregate Stability after Nineteen Years of Rice–Wheat Cropping System

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**Abstract:** Continuing soil degradation remains a serious threat to future food security. Soil aggregation can help protect soil organic matter from biodegradation; it affects soil physical (aeration), chemical (water infiltration), and biological (microbial) activities. The integrated plant nutrition system (IPNS) and organic farming (OF) options have been contemplated as a sustainable strategy to sustain soil aggregate stability under adverse climatic conditions and a possible tool to restore degraded soil systems. Results suggested that the application of plant nutrients based on IPNS and soil test crop response (STCR) including mineral fertilizers and organic manure (farmyard manure: FYM) improved soil aggregate stability and mean weight diameter (MWD) under rice–wheat cropping systems. A long-term (19 year) cropping system (rice–wheat) experiment was examined to identify best nutrient management practices. Seven nutrient supply options were applied: organic, mineral fertilizer in combination with IPNS, IPNS + B/IPNS + C to improve soil aggregate stability and MWD after completing 19 cropping cycles of rice–wheat cropping systems. Results showed that significantly higher (+31%) macroaggregates were dominant in the surface soil layer than in the subsurface soil. The significantly highest macroaggregates were observed under OF (60.12 g 100 g$^{-1}$ dry soil) management practices followed by IPNS options. The MWD was significantly increased (+17%) between surface and subsurface soil. Maximum MWD was reported with OF (0.93 mm) management practices followed by the IPNS + C (0.78 mm), IPNS + B (0.77 mm), IPNS (0.70 mm), STCR (0.69 mm), NPK (0.67 mm), and unfertilized control (0.66 mm) plots. Overall, results suggest that the adoption of IPNS options, such as organic farming (OF), RDF, STCR, and inclusion of pulses (berseem and cowpea), significantly improved all soil aggregation fractions in the soil system and also offered an additional benefit in terms of soil sustainability.

**Keywords:** nutrient supply options; soil aggregation; aggregation stability; organic manure; mineral fertilizer

## 1. Introduction

The global food system will encounter an unprecedented convergence of pressures over the next few decades. Soil degradation is considered one of the main causes of stagnating productivity growth. Soil aggregate stability improves soil quality, porosity, nutrient and water storage capacity, and food production, as well as decreases soil and nutrient loss. Soil aggregates, especially water stable aggregates, are of special importance for high water infiltration and good soil structure. These properties help determine soil quality and directly influence water-energy and food nexus. Soil aggregate stability can be used as combined index to maintain nutrients holding capacity and soil sustainability [1,2], which help to maintain agroecosystem sustainability [3,4]. Soil aggregates are the fundamental indicators of soil structure and store plant nutrient, which help the growth and development of plants [5–7]. Intensive agriculture management practices are exposed to land degradation. The improvement of soil aggregate stability is vital to strengthen the management value of degraded land of subtropical and tropical regions [8,9].

Crop yields will continue to be vitally important in the fight to achieve global food security, and the soil offers a great opportunity to boost crop production by enhancing the natural interaction between the soil and crops. Judicious application of organic manures and inorganic fertilizers accelerate soil aggregation and improve the organic matter in agriculture soils [10,11]. Instabilities of soil structure through mismanagement of tillage, nutrients, and agrochemicals can result in low soil quality, loss of soil and nutrients, reduce water availability, and degraded the soil quality [2,12,13]. Mostly, soil aggregate stability can be promoted by higher concentrations of carbon, mean weight diameter (MWD), and water-stable aggregates [2,14,15].

Intensive management practices have been considered a key factor in monitoring, regulating, stabilizing, and restoring the soil ecosystem [16–18]. The mismanagement of agricultural practices are one of the major causes of land degradation [19]; there are four types (i) physical (soil structure), (ii) chemical (soil fertility), (iii) biological (soil biodiversity), and (iv) ecological (all three factors lead to this) agroecosystem sustainability [20]. In the last few decades, there has been unparalleled interest and research attempts in finding adaptive management practices to efficiently restore degraded ecosystems [21–23].

Minimum soil disturbances, balanced application of organic manure and mineral fertilizers, preservation soil covers, and adoption of pules and green manuring crops in cropping systems, had positive impacts on soil aggregate stability by restoring degraded land, which in turn lead to superior crop growth development [22,24–26].

Despite its encouraging possibility, the IPNS options in rice–wheat cropping systems are limitedly adopted by farmers due to the insufficient support and impact assessment. Hence, to implement, design, and adopt the most effective IPNS options towards optimizing the soil aggregate stability, it is vital to launch efficient regulating, monitoring, and restoring assessments of soil aggregate stability and food security. The proportion of soil particles sequestered in aggregates contributes to the movement and storage of water, soil aeration, and species composition and distribution of soil organisms.

Moreover, there is a lack of studies in the literature about different nutrient supply options that evaluated the impacts of IPNS options, STCR, and OF practices on soil aggregate stability and soil sustainability. Consequently, developing our knowledge of the relationships between macroaggregate, microaggregate, and mean weight diameter under long-term applications of different nutrient supply options at aggregate scales is crucial for increasing aggregate stability and soil sustainability. Thus, it could be understood that changing soil quality induced by IPNS options, STCR, and OF practices would provide more scientific indications in evaluating soil aggregate stability. Hence, it is urgent to improve aggregation stability by adopting integrated plant nutrition system (IPNS) supply options (inclusion of pulses), soil test crop response (STCR), and organic farming (OF) practices, to maintain aggregate stability and soil quality.

Some fundamental questions remain unexplored, such as (i) how do IPNS options influence macroaggregate and microaggregate?; (ii) does organic manure application influence different soil aggregation fractions?; (iii) does IPNS and pulses (berseem and cowpea) options alleviate the adverse effect of climatic factors on soil aggregate stability?; and (iv) how does the relationship of different soil aggregation fractions influences MWD under rice–wheat cropping systems? Therefore, the effects of long-term application of IPNS options, STCR, and OF practices were tested to appraise their impact on soil aggregate stability after the completion of 19 cropping system cycles.

Based on the literature discussed above and the questions raised here, we hypothesized that in IPNS options, STCR and OF practices could increase or decrease the soil aggregate stability. Consequently, we intend to elucidate long-term IPNS options' effects (i) to quantify the IPNS options and soil depths on soil aggregation fractions and (ii) to assess the best nutrient supply options and quantitative aggregate stability, MWD, and relationship compared to different nutrient supply options in long-run with a broad view to assess optimum options to maintain soil sustainability.

## 2. Materials and Methods

### *2.1. Site Descriptions*

The ongoing long-term experimental site of ICAR-Indian Institute of Farming Systems Research Meerut is situated at 29°4′ N, 77°46′ E, 237 m above sea level located in the Western part of Uttar Pradesh, represents an irrigated, mechanized, and input-intensive cropping area of the Upper Gangetic Plain (UGP) transect of the Indo-Gangetic Plain (IGP). This long-term field experiment was started in 1998 to identify "Sustainable Production Model for Rice-Wheat Cropping System" on a sandy loam soil representing AEZ 4.1 (Hot semi-arid eco-region). Initial soil characteristics are presented in Table 1.

**Table 1.** Initial soil properties of experimental site (1998).

| Soil Characteristics | Type/Values |
|---|---|
| Texture Clay | Sandy loam |
| Sand (g kg$^{-1}$) | 62.90 |
| Silt (g kg$^{-1}$) | 19.30 |
| Clay (g kg$^{-1}$) | 17.80 |
| **Bulk density (Mgm$^{-3}$)** | |
| 0–15 cm | 1.49 |
| 15–30 cm | 1.52 |
| **pH (1:2, soil/water)** | |
| 0–15 cm | 8.01 |
| 15–30 cm | 7.89 |
| **EC (dSm$^{-1}$)** | |
| 0–15 cm | 0.11 |
| 15–30 cm | 0.12 |
| **Organic carbon (g kg$^{-1}$)** | |
| 0–15 cm | 5.10 |
| 15–30 cm | 3.60 |

### *2.2. Climatic Features of the Experimental Site*

The climate of the experimental site is semi-arid subtropical, with dry hot summers and cool winters. The average monthly minimum and maximum temperatures in January (the coolest month) are 7.2 °C and 20.1 °C, respectively. The corresponding temperatures in May (the hottest month) are 24.2 °C and 39.8 °C, respectively. Average annual rainfall is 823 mm out of which ~75% rainfall is received through the South-west monsoon during July–September month (Supplementary Table S1).

### *2.3. Treatments and Experimental Design*

The long-term cropping system experiment at an involving different nutrient supply options under rice-wheat rotation (Figure 1). The experiment was conducted in large plots (individual plot area 1000 m$^2$). All treatments were Randomized Block Design (RBD) and four replications. Treatments for a total of seven nutrient supply options were used in the long-term cropping system experiment as $T_1$: control i.e., no chemical fertilizer or organic manure; $T_2$: recommended fertilizer dose to rice and wheat; $T_3$: soil-test based fertilizer application in both crops; $T_4$: 75% of recommended N, P, and K through fertilizers +25% substitution of recommended N through FYM in rice and RDF in wheat crop; $T_5$: 75% of recommended N, P, and K through fertilizers + 25% substitution of recommended N through FYM + every third wheat substituted with berseem for rice and RDF for wheat crop; $T_6$: 75% of recommended N, P, and K through fertilizers + 25% substitution of recommended N through FYM + every third rice substituted with cowpea for rice and RDF for wheat crop; and $T_7$: 100% of recommended N, P, and K through organic manures (FYM) in both crops. Experimental photographs during Kharif season (Figure 2).

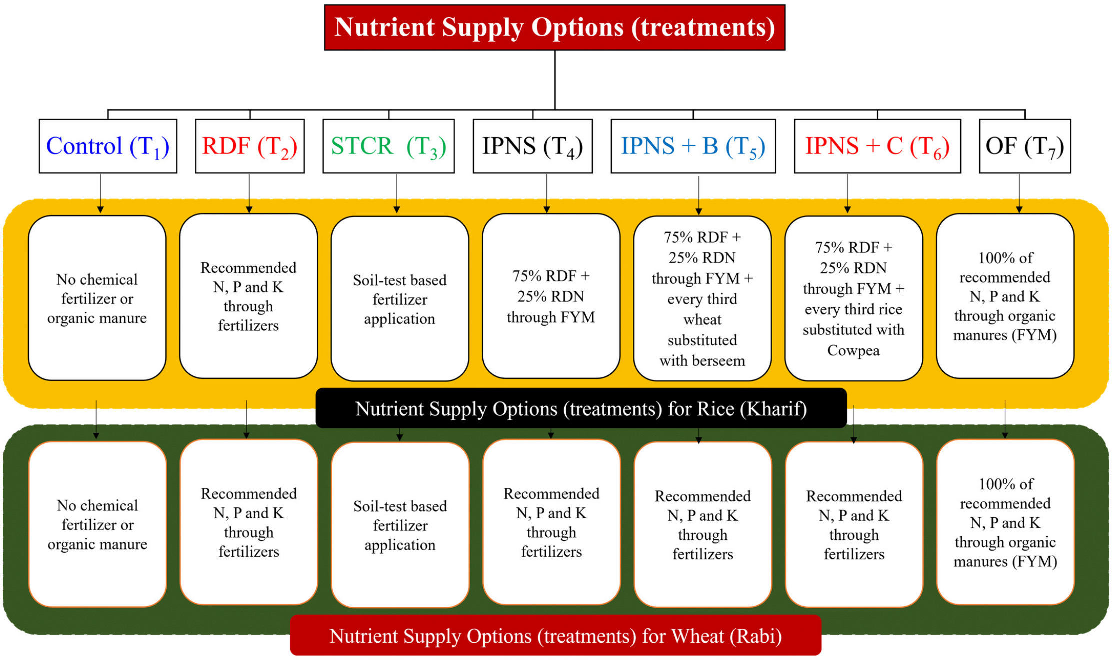


**Figure 1.** Experimental setup and treatment details for different nutrient supply options for rice–wheat cropping system.

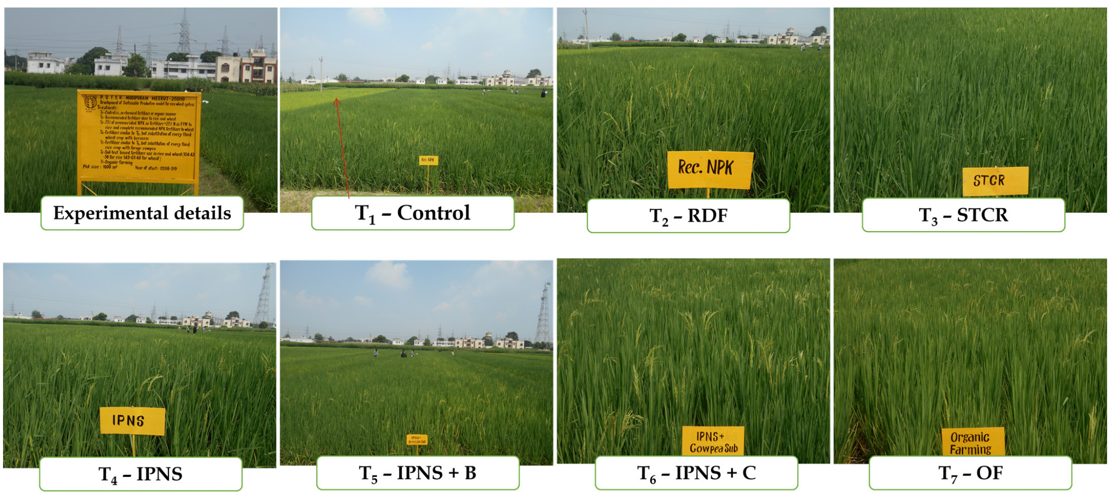


**Figure 2.** Experimental view during the Kharif season (rice) sowing all treatment combination.

### 2.4. Collection and Processing of Soil Samples

After the completion of 19 cropping cycles at ICAR-IIFSR, Modipuram, Meerut, four sets of replicated samples of both surface (0–15 cm) and sub-surface (15–30 cm) soil layers were collected from all treatments during May 2017 using a core sampler (with a core of 3.9 cm diameter and 179.2 $cm^3$ volume). The soil samples were collected after 19 cropping cycles of the rice–wheat cropping system were completed. The first set was used to measure soil bulk density. From the second set of undisturbed soil samples, a set of sub-samples was taken for the determination of soil aggregate fractionations (Figure 3).

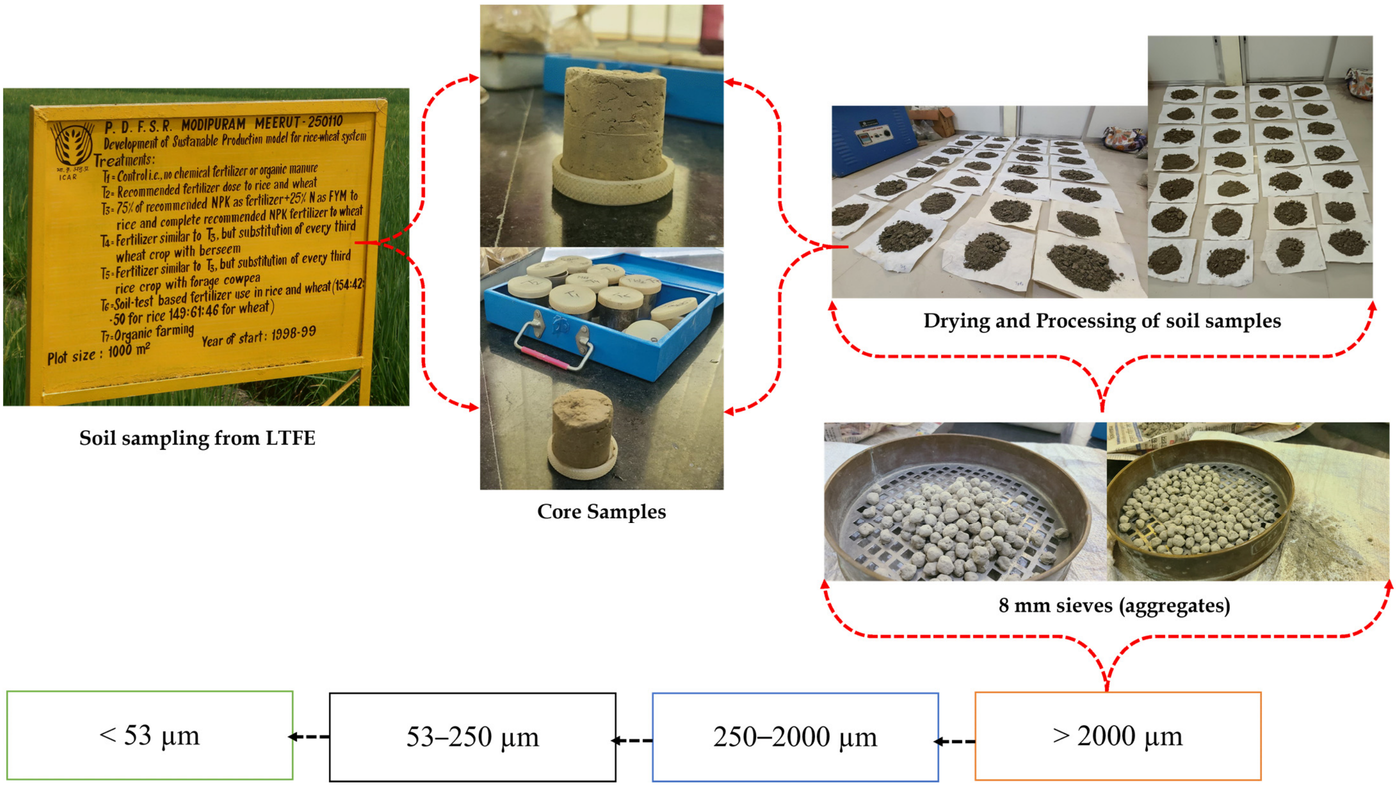


**Figure 3.** Experimental photographs of the soil samples used in the analysis.

### 2.5. Soil Aggregate Fractions Separation

Briefly, to obtain four soil fractions, 100 g air dried (4.75-mm sieved) soil sample was placed on the top of a 2-mm sieve (Figure 4). A series of three sieves (2000, 250, and 53 µm) was used to obtain four aggregate fractions: (i) >2000 µm; (ii) 250–2000 µm; (iii) 53–250 µm; (iv) and <53 µm (silt and clay particles) [27]. Small and large macroaggregates together constitute the macroaggregates. Sieving was done mechanically using a modified Yodar apparatus that moved the sieve up and down 3 cm, 50 times in 2 min to achieve aggregate separation [28].

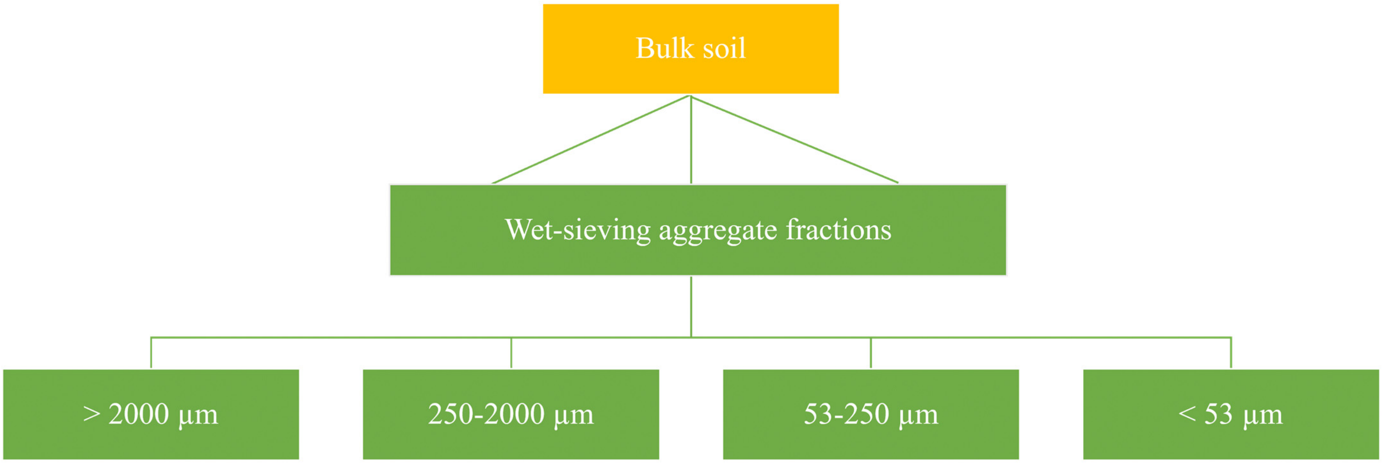


**Figure 4.** Soil aggregation fractionation schemes used to obtain aggregates and subfractions within microaggregate and microaggregates.

*2.6. Mean Weight Diameter (MWD)*

Mean weight diameter (MWD) was calculated using the procedure given by Van Bavel [29] where four aggregate fractions {>2000 µm, 250–2000 µm, 53–250 µm, and <53 µm (silt and clay particles)} were considered.

$$MWD = \frac{\sum_{i=1}^{n} \overline{x}_i}{\sum_{i=1}^{n} w_i}$$

$\overline{x}_i$—Mean diameter of different sizes of aggregates.
$w_i$—Proportion of different sizes of aggregates to total weight of aggregate

*2.7. Data Analyses*

The produced data was treated for analysis of variance (ANOVA) and Duncan's multiple range test (DMRT) $p < 0.05$ [30] was performed to test statistical differences in soil aggregation fractions (i) >2000 µm; (ii) 250–2000 µm; (iii) 53–250 µm; (iv) and <53 µm, macroaggregate, microaggregate, and mean weight diameter between different treatment combinations and soil depth. To check the data normality, Shapiro–Wilks test were performed. The relationship among macroaggregate, microaggregate, and mean weight diameter of both soil layers were described by linear regression functions.

## 3. Results

*3.1. Aggregate-Size (>2000 µm) Distribution*

Data indicated that the significant differences in aggregate size fractions were found across the different nutrient management practices and soil depths of rice–wheat cropping systems (Tables 2 and 3). Organic farming (OF) treatment contained larger >2000 µm (20.79 and 13.68 g 100 $g^{-1}$ dry soil) followed by the IPNS + C (16.61 and 12.48 g 100 $g^{-1}$ dry soil), it was on par with IPNS + B (16.08 and 12.54 g 100 $g^{-1}$ dry soil), although the differences in the IPNS/STCR and NPK/unfertilized control were not statistically significant in the 0–15 and 15–30 cm soil depth, respectively. This increase in the >2000 µm might be due to higher organic carbon concentration in OF options, in which recommended doses of nutrients were applied through FYM in both cropping seasons (Tables 2 and 3).

**Table 2.** Soil aggregation distribution as affected by long-term nutrient supply options of rice–wheat system in the 0–15 cm soil layer. Means of different treatments followed by the different lower-case letter are significantly different at $p < 0.05$ level of significance according to DMRT.

| Treatments | Size Distribution of Aggregates, μm | | | |
|---|---|---|---|---|
| | >2000 | 250–2000 | 53–250 | <53 |
| | g 100 g$^{-1}$ Dry Soil | | | |
| Control | 13.0 $^{d}$ | 31.8 $^{e}$ | 48.0 $^{a}$ | 7.2 $^{d}$ |
| NPK | 13.3 $^{d}$ | 32.9 $^{de}$ | 46.1 $^{a}$ | 7.8 $^{d}$ |
| STCR | 14.0 $^{cd}$ | 33.8 $^{cde}$ | 41.8 $^{b}$ | 10.4 $^{c}$ |
| IPNS | 14.2 $^{cd}$ | 36.5 $^{bcd}$ | 38.5 $^{b}$ | 10.9 $^{c}$ |
| IPNS + B | 16.1 $^{bc}$ | 37.5 $^{abc}$ | 33.4 $^{c}$ | 13.0 $^{b}$ |
| IPNS + C | 16.6 $^{b}$ | 37.9 $^{ab}$ | 32.0 $^{c}$ | 13.6 $^{ab}$ |
| OF | 20.8 $^{a}$ | 39.3 $^{a}$ | 25.2 $^{d}$ | 14.7 $^{a}$ |

**Table 3.** Soil aggregation distribution as affected by long-term nutrient supply options of rice-wheat system in the 15–30 cm soil layer. Means of different treatments followed by the different lower-case letter are significantly different at $p < 0.05$ level of significance according to DMRT.

| Treatments | Size Distribution of Aggregates, μm | | | |
|---|---|---|---|---|
| | >2000 | 250–2000 | 53–250 | <53 |
| | g Aggregate 100 g$^{-1}$ Dry Soil | | | |
| Control | 8.5 $^{d}$ | 41.0 $^{d}$ | 44.4 $^{a}$ | 6.1 $^{d}$ |
| NPK | 9.9 $^{cd}$ | 41.9 $^{cd}$ | 41.2 $^{ab}$ | 7.0 $^{d}$ |
| STCR | 10.4 $^{bcd}$ | 42.7 $^{bcd}$ | 38.8 $^{ab}$ | 8.2$^{c}$ |
| IPNS | 11.3 $^{abcd}$ | 44.3 $^{abcd}$ | 35.5 $^{bc}$ | 8.8 $^{b}$ |
| IPNS + B | 12.5 $^{abc}$ | 46.1 $^{abc}$ | 32.2 $^{c}$ | 9.2 $^{a}$ |
| IPNS + C | 12.8 $^{ab}$ | 46.6 $^{ab}$ | 31.8 $^{c}$ | 8.8 $^{b}$ |
| OF | 13.7 $^{a}$ | 47.7 $^{a}$ | 30.6 $^{c}$ | 8.1 $^{c}$ |

### *3.2. Aggregate-Size (250–2000 μm) Distribution*

Results observed that the 250–2000 μm fraction of aggregation was significantly higher under OF (39.33 g 100 g$^{-1}$ dry soil) management followed by the IPNS + C (37.86 g 100 g$^{-1}$ dry soil), IPNS + B (37.54 g 100 g$^{-1}$ dry soil), IPNS (36.47 g 100 g$^{-1}$ dry soil), STCR (33.76 g 100 g$^{-1}$ dry soil), NPK (32.85 g 100 g$^{-1}$ dry soil), and the lowest values were found in the control (31.77 g 100 g$^{-1}$ dry soil) plot in surface (0–15 cm) soil. A similar trend was also observed in the subsurface (15–30 cm) soil (Tables 2 and 3).

### *3.3. Aggregate-Size (53–250 μm) Distribution*

Tables 2 and 3 showed that significantly higher soil aggregation distributions (53–250 μm) were observed under NPK and unfertilized plot, followed by STCR/IPNS and IPNS + C/IPNS + B; on the other hand, the lowest value of 53–250 μm fraction of soil aggregation was observed with OF management in both soil depth in both soil layer. At 0–15 cm soil depth, the highest 53–250 μm fractions were observed in control (47.99 g 100 g$^{-1}$ dry soil) and NPK (46.05 g 100 g$^{-1}$ dry soil), which was on par with control and STCR and IPNS (41.77 and 38.47 g 100 g$^{-1}$ dry soil), respectively. In contrast, the significantly lowest values were recorded for the OF option (25.20 g 100 g$^{-1}$ dry soil). However, in the case of 15–30 cm soil layer, 53–250 μm fractions sizes were reported in the following order:

control > NPK ≥ STCR > IPNS > IPNS ≥ IPNS + B ≥ IPNS + C ≥ OF under different nutrient supply options.

*3.4. Aggregate-Size (<53 µm) Distribution*

A significantly higher <53 µm size fraction was found in OF (14.67 g 100 $g^{-1}$ dry soil); it was on par with IPNS + C (13.56 g 100 $g^{-1}$ dry soil), followed by IPNS + B (12.96 g 100 $g^{-1}$ dry soil), IPNS (10.88 g 100 $g^{-1}$ dry soil), STCR (10.43 g 100 $g^{-1}$ dry soil), NPK (7.79 g 100 $g^{-1}$ dry soil), and control (7.72 g 100 $g^{-1}$ dry soil) treatment in 0–15 cm soil depth. In the case of subsurface soil, results were observed in the following order: IPNS + B > IPNS > IPNS + C > STCR > OF > NPK, and control treatment (Tables 2 and 3). In contrast to the other sizes of soil aggregation, the significantly highest <53 µm were found for OF options followed by the IPNS options, and the lowest were found for the control and NPK options.

*3.5. Macroaggregates Distribution*

Data revealed that both (macro and micro) aggregates significantly varied among the different nutrient management practices in both soil depths over the periods (Figures 5 and 6). Macroaggregates significantly varied from 44.79 to 60.12 and 49.50 to 61.34 g 100 $g^{-1}$ dry soil in the surface and subsurface soil layers, respectively. Macroaggregates accounted for ~31% of the total aggregates and were more dominant in the surface soil layer than the subsurface soil layer. Maximum macroaggregates were observed under OF (60.12 g 100 $g^{-1}$ dry soil) management practices followed by IPNS + C (54.47 g 100 $g^{-1}$ dry soil), IPNS + B (53.62 g 100 $g^{-1}$ dry soil), IPNS (50.66 g 100 $g^{-1}$ dry soil), STCR (49.49 g 100 $g^{-1}$ dry soil), and NPK (46.16 g 100 $g^{-1}$ dry soil), and lower values (44.79 g 100 $g^{-1}$ dry soil) were reported for the unfertilized control plot. Having said that, the results of macroaggregates fractions under 15–30 cm soil depth were reported in the following order: OF > IPNS + C > IPNS + B > IPNS > STCR > NPK, and the lowest values were found for the unfertilized control plot (Figure 5).

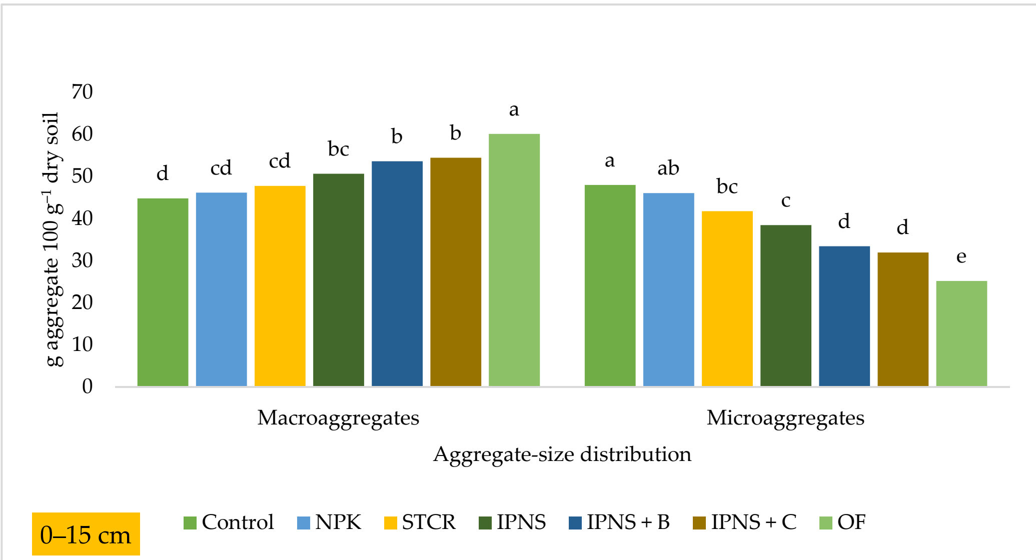


**Figure 5.** Effect of long-term nutrient supply options on macroaggregate and microaggregate fractions in the 0–15 cm soil layer of a rice–wheat cropping system. Means of different treatments followed by the different lower-case letters are significantly different at $p < 0.05$ level of significance according to DMRT.

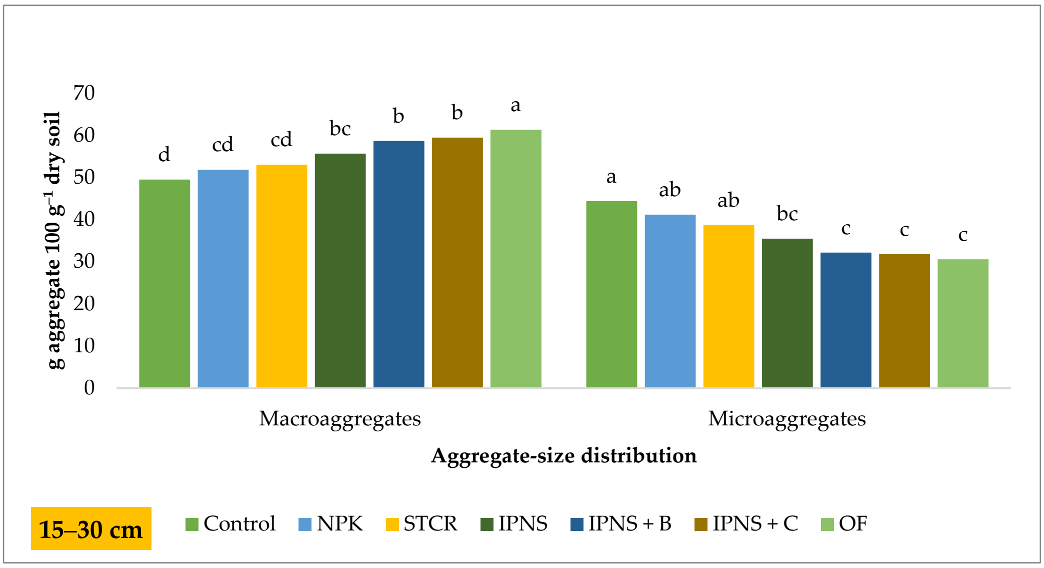


**Figure 6.** Effect of long-term nutrient supply options on macroaggregate and microaggregate fractions in the 15–30 cm soil layer of a rice–wheat cropping system. Means of different treatments followed by the different lower-case letters are significantly different at $p < 0.05$ level of significance according to DMRT.

In macroaggregates, OF (60.12 and 61.34 g 100 g$^{-1}$ dry soil) and IPNS + C (54.47 and 59.47 g$^{-1}$ dry soil) had significantly larger aggregate fractions than NPK (46.16 and 51.82 g 100 g$^{-1}$ dry soil) and unfertilized control (44.79 and 49.50 g 100 g$^{-1}$ dry soil) treatment in 0–15 and 15–30 cm soil depths, respectively.

### *3.6. Microaggregates Distribution*

The results of microaggregates varied from 25.20 to 47.99 and 30.57 to 44.39 g 100 g$^{-1}$ dry soil in 0–15 and 15–30 cm soil depth, respectively. Significantly highest (47.99 g 100 g$^{-1}$ dry soil) values were reported for the unfertilized control plot; this was on par with the NPK-treated (46.05 g 100 g$^{-1}$ dry soil) plot, followed by the STCR (41.77 g 100 g$^{-1}$ dry soil), IPNS (38.47 g 100 g$^{-1}$ dry soil), IPNS + B (33.42 g 100 g$^{-1}$ dry soil), and IPNS + C (31.97 g 100 g$^{-1}$ dry soil), and the lowest (25.20 g 100 g$^{-1}$ dry soil) values were reported for OF management practices in 0–15 cm soil depth. Similar trends were also reported in subsurface soil of the rice–wheat cropping system over the periods (Figure 6).

In contrast to what was observed for large and small macroaggregates, NPK (46.05 and 41.19 g 100 g$^{-1}$ dry soil) and unfertilized control (47.99 and 44.39 g 100 g$^{-1}$ dry soil) had a significantly higher quantity of microaggregates than OF (25.20 and 30.57 g 100 g$^{-1}$ dry soil) and IPNS + C (31.97 and 31.78 g 100 g$^{-1}$ dry soil) in 0–15 and 15–30 cm soil depth, respectively.

### *3.7. Mean Weight Diameter (MWD)*

Mean weight diameter (MWD) was estimated as measures of soil aggregate stability, and it was significantly affected by various nutrient management treatments over the periods (Figure 7). The MWD was significantly increased (+17%) between surface and subsurface soil. The proportion of MWD of the surface soil was significantly increased compared with the subsurface soil. MWD significantly varied from 0.66 to 0.93 and 0.53 to 0.78 mm in the 0–15 and 15–30 cm soil depth, respectively. Maximum MWD was reported for OF (0.93 mm) management practices, followed by the IPNS + C (0.78 mm), IPNS + B (0.77 mm), IPNS (0.70 mm), STCR (0.69 mm), NPK (0.67 mm), and unfertilized control (0.66 mm) plots. Consequently, in 15–30 cm soil depth, the maximum values were observed for OF (0.78 mm), followed by IPNS + C (0.68 mm), IPNS + B (0.67 mm), IPNS (0.63 mm), STCR (0.59 mm), and NPK (0.58 mm), and the significantly lowest (0.53 mm) values were reported for the unfertilized control plot. The plots with OF management showed significant superiority over the rest of the treatment areas; its superiority was ~29% and 32% higher than the control treatment in the 0–15 and 15–30 cm soil depth, respectively (Figure 7).

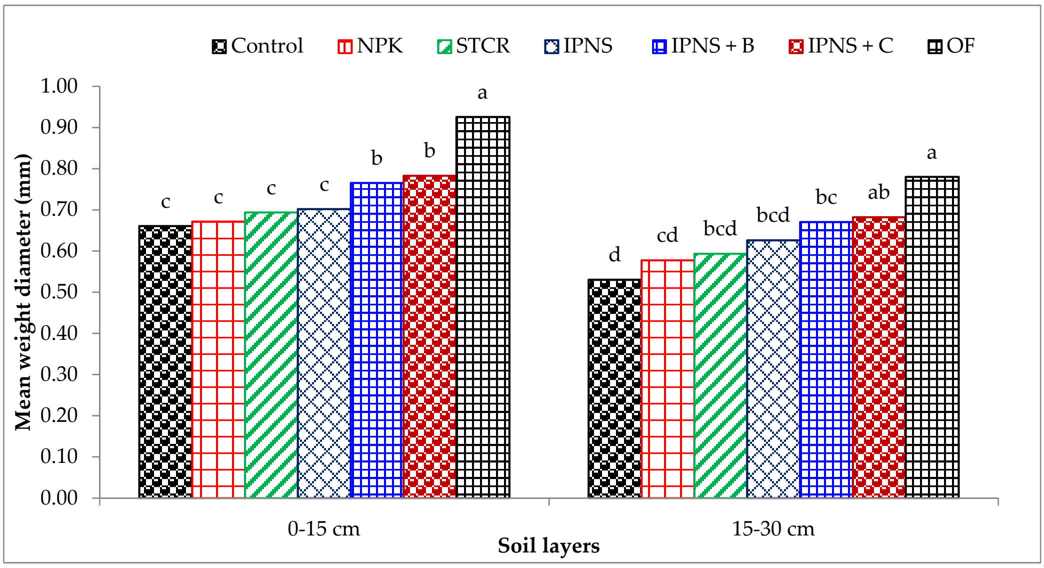


**Figure 7.** Effect of long-term nutrient supply options on mean weight diameter in the 0–15 and 15–30 cm soil layer of rice–wheat system. Means of different treatments followed by the different lower-case letters are significantly different at $p < 0.05$ level of significance according to DMRT.

### *3.8. Relationship between Macroaggregate, Microaggregate, and Mean Weight Diameter*

The macroaggregate, microaggregate fractions, and mean weight diameter have often been used as indices of soil sustainability. Results showed that macroaggregates were significantly negatively correlated with microaggregates ($R^2 = 0.99$, $p < 0.01$; Figure 8a) in 0–15 cm soil depth and in 15–30 cm soil depth ($R^2 = 0.98$, $p < 0.01$; Figure 8b). The regression lines for macroaggregates versus microaggregates showed a negative linear relationship (macroaggregate = $-1.5067x + 114.81$ and $-1.1895x + 102.53$) in the 0–15 and 15–30 cm soil depth.

In the case of macroaggregates with mean weight diameter, the results showed a strong positive relationship ($R^2 = 0.93$, $p < 0.01$; Figure 9a) in 0–15 cm soil depth and in 15–30 cm soil depth ($R^2 = 0.92$, $p < 0.01$; Figure 9b).

The regression lines for macroaggregate versus MWD showed a positive linear relationship (macroaggregate = $54.839x + 10.35$ and $51.477x + 22.849$) in the 0–15 and 15–30 cm soil depth. However, microaggregates and MWD had a significantly strong negative relationship ($R^2 = 0.89$, $p < 0.01$; Figure 10a) in 0–15 cm soil depth and in 15–30 cm soil depth ($R^2 = 0.86$, $p < 0.01$; Figure 10b).

The regression lines for microaggregate versus MWD showed a negative linear relationship (microaggregate = $-81.148x + 98.12$ and $-59.61x + 74.318$) in the 0–15 and 15–30 cm soil depth (Figure 10a,b).

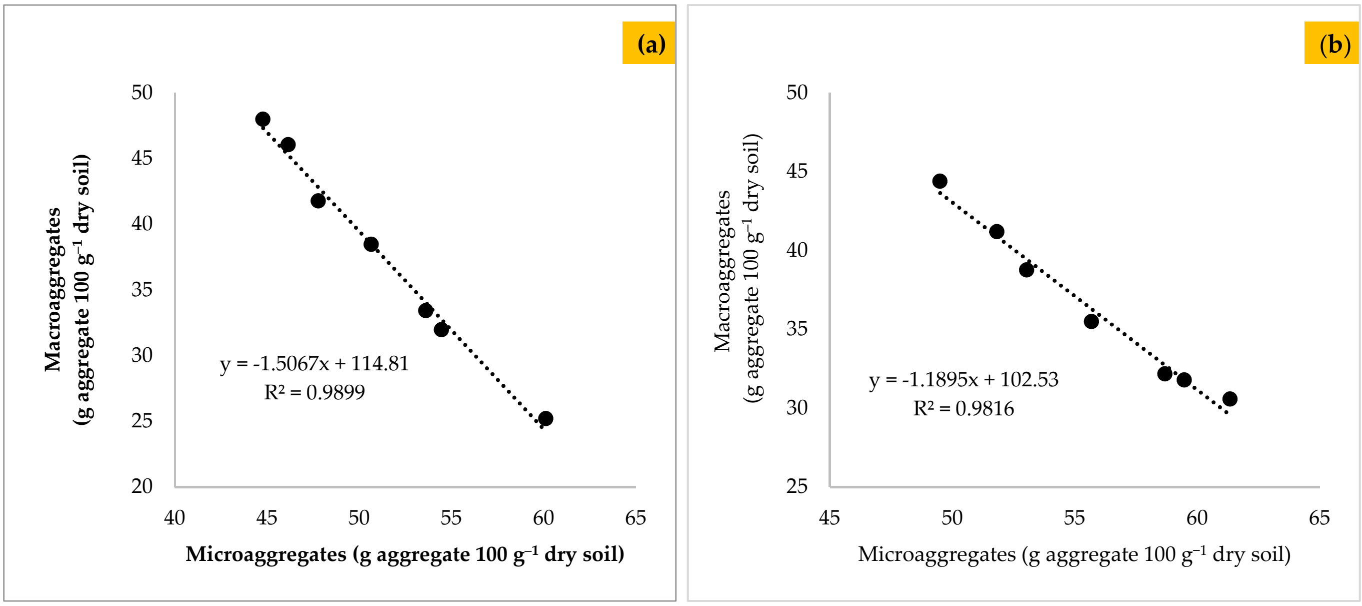


**Figure 8.** Relationship between microaggregate and macroaggregate fractions of soil aggregation; (**a**) 0–15 cm and (**b**) 15–30 cm soil depths.

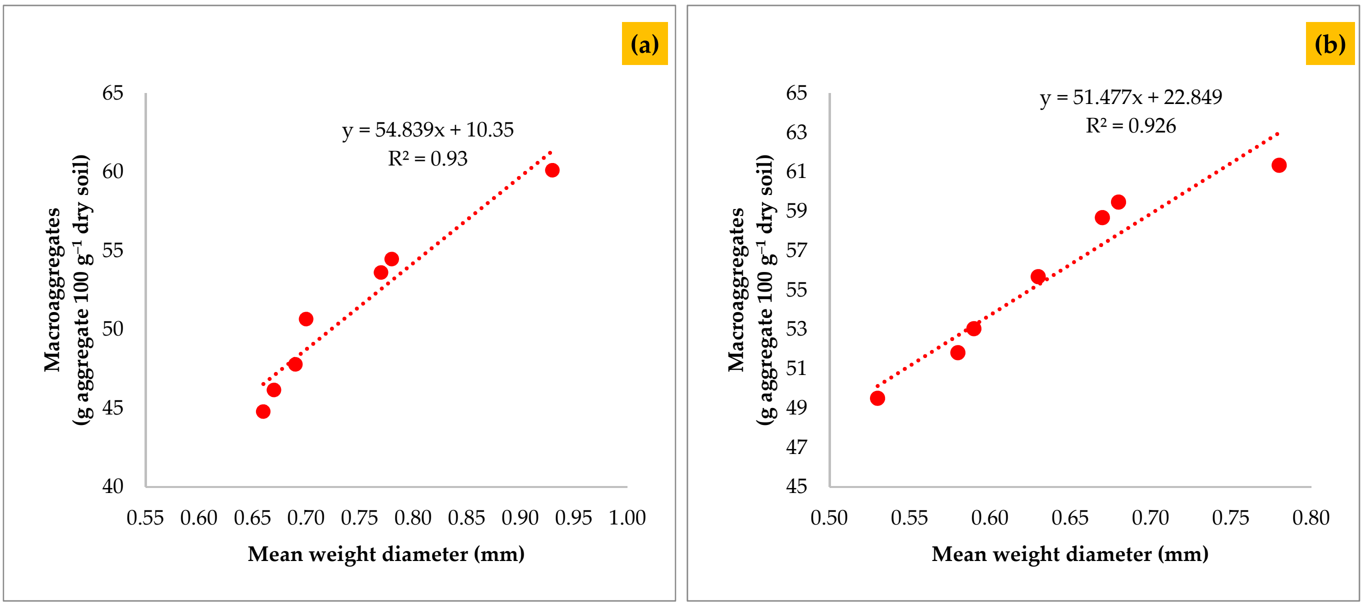


**Figure 9.** Relationship between macroaggregate and mean weight diameter fractions of soil aggregation; (**a**) 0–15 cm and (**b**) 15–30 cm soil depths.

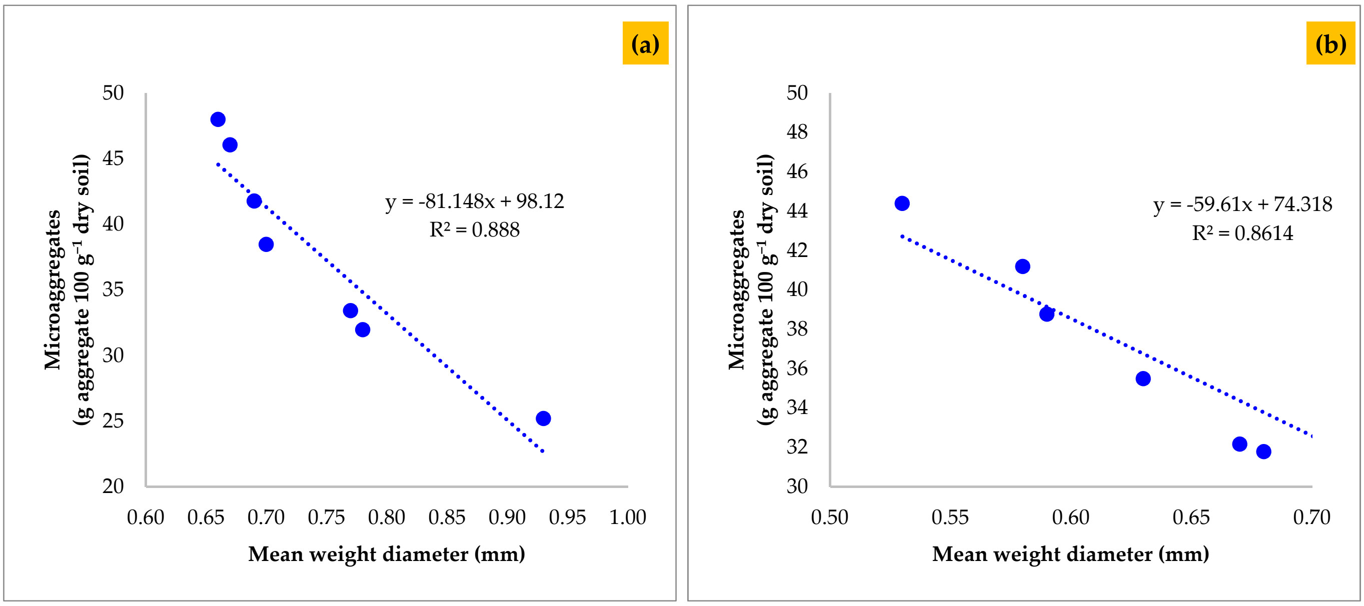


**Figure 10.** Relationship between microaggregate and mean weight diameter fractions of soil aggregation; (**a**) 0–15 cm and (**b**) 15–30 cm soil depths.

## 4. Discussion

### *4.1. Aggregate-Size Distribution*

Soil aggregate fraction and stability of aggregates can be used as a combined index to maintain nutrients holding capacity and agroecosystem sustainability [1,4]. The judicious application of organic manures and inorganic fertilizers accelerates soil aggregation [1] and improves organic matter in agriculture soils [10,11]. The increase in the size of aggregates might be due to higher organic carbon concentration in OF options, in which recommended doses of nutrients were applied through FYM in both cropping seasons (Tables 2 and 3). The addition of higher organic matter might have a cementing effect, aggregating and nutrient cycling, which helps to promote crop growth and development [31–33].

OF and all the IPNS options, IPNS + B, IPNS + C, and IPNS showed significant superiority over the STCR, NPK, and control plot. This might be due to the higher concentration of carbon and inclusion of legumes (berseem and cowpea), which help to improve soil sustainability. The soil depth's influence on these processes increased with judicious use of organic manure and mineral fertilizers [34–36].

Our study results support the notion that the judicious application of organic manure and mineral fertilizers significantly improves soil aggregations, as it promotes a higher concentration of organic matter [33,34]. Nevertheless, the impact of this same technology may differ with different soil types. Similarly, significantly higher soil aggregation fractions (53–250 µm) and aggregate stability were associated with the judicious application of animal and chicken manure [36–38]. Jiang et al. [39] and Ghosh et al. [34] also suggested that silt + clay had higher carbon concentrations. We also found that silt + clay fractions were highest in OF options. This might be due to the application of organic manure that works as a cementing agent and helps to promote the formation of aggregations [5,36,40]. Soil organic matter and soil water content significantly influenced the aggregate stability of soils with contrasting cropping histories [41–45]. A significant relation between aggregate breakdown, crusting, and water erosion were observed [46]. The use of organic matter has positive influences on both soil aggregation and aggregate stability [41,42,47].

### *4.2. Micro- and Macroaggregates Distribution*

Results showed that both aggregate fractions significantly varied among the different nutrient management practices in both soil depth over the periods (Figures 5 and 6).

Significantly higher quantities of macroaggregates were observed in OF, followed by IPN + C/IPNS + B, which had positive impacts on aggregation [3,31]; this might be due to higher carbon concentrations that help as a cementing agent during the formation of macroaggregates [48,49]. Results showed that the IPNS and OF options had a higher quantity of macroaggregates than microaggregates after completing 19 cropping system cycles (Figures 5 and 6). The significantly higher quantities of macroaggregates than microaggregates could be due to the lesser amount of soil organic carbon, and the non-addition of organic manure [35,36].

### *4.3. Mean Weight Diameter (MWD)*

Aggregate stability was significantly affected by various nutrient management treatments over the periods (Figures 5 and 6). Plots with OF management showed its significant superiority over the rest of the treatments in both soil layers (Figure 7). In subsurface soil, the decreased MWD was driven by the change in aggregate distribution, especially for the disintegration of large macroaggregates into microaggregates, which indicated the presence of aggregates with higher stability in OF management practices in comparison with the rest of the treatment combinations under long-term fertilization; macroaggregates also directly correlated with MWD [36,40,50]. Results suggest that higher soil organic matter content may be responsible for relatively higher percentage aggregation, larger median aggregate size, and more kinetic energy required to disrupt aggregates as compared to plow-tillage treatments. Similarly, our results corroborate that aggregate stability as measured by MWD was significantly macroaggregate [51,52].

### *4.4. Relationship between Macroaggregate, Microaggregate and MWD*

Macroaggregates significantly negatively correlated with microaggregates in both soil layers (Figure 8a,b). In contrast, macroaggregates with mean weight diameter results showed a strong positive relationship in the 0–15 cm soil depth and in 15–30 cm soil depth (Figure 9a,b). However, in the case of microaggregates and MWD, there was a significantly strong negative relationship for both soil depths (Figure 10a,b). A significant increase in aggregate stability was found when adopting IPNS and OF options and adding organic manure; organic input directly contributed to SOC and works as a cementing agent between the soil particles [36,53,54]. Soil management practices also significantly influenced soil properties under rainfed lowland rice-based cropping systems [55].

Our results suggest that the adoption of IPNS options (berseem and cowpea) and organic farming had a significant role in improving the aggregate stability. This can alter how IPNS and OF options affect aggregate stability. Consequently, it is crucial to study the effects of best management practices (NPK, STCR, IPNS, IPNS + B, IPNS + C, and OF) on aggregate size distribution (micro- and macro-aggregate) and mean weight diameter in rice–wheat cropping systems after the completion of 19 cropping cycles. Soil fungi and organic matter significantly influenced plant nutrition and soil aggregate formation [56], and similarly increased mycorrhizal associations, soil aggregation, and the weathering of minerals [57]. However, a decline in soil organic matter levels lead to a decrease in soil aggregate stability and infiltration rates, and an increase in susceptibility to compaction, run-off, and erosion [58]. The results suggested that the soil structure characteristics (macro and micro aggregates) along the climatic transect are non-linear [59]. Soil structure influences soil water movement and retention, erosion, crusting, nutrient recycling, root penetration, and crop yield [60–62], soil aggregates are one component of soil structure [63–66].

## 5. Conclusions and Recommendations

The long-term (19-year) combined application of organic manure, mineral fertilizer, and adoption of integrated plant nutrition system (IPNS) options, significantly improved soil aggregate stability with higher mean weight diameter (MWD) and macroaggregates. MWD was significantly positively correlated with macroaggregate in the long run. In addition, MWD was increased (+17%) with organic farming (OF) options and with

IPNS + C, IPNS + B, and STCR. Therefore, the adoption of IPNS and OF options could provide better nutrient management practices in improving soil aggregate stability after the completion of 19 cropping system cycles. We concluded that the adoption of organic farming options improves soil aggregate stability and MWD, followed by IPNS options for long-term rice–wheat cropping systems.

We also found that certain nutrient management strategies (STCR, OF, IPNS + berseem and cowpea) have the potential for maintaining soil aggregate stability. When legumes (cowpea and berseem) were grown every three years, the nutrient availabilities to plants were positive in both IPNS options. At the level of legume inclusion, berseem (+12%) and cowpea (+14%) were reported compared to the control plot after the completion of 19 cropping system cycles. Overall, the results suggest that innovative IPNS and OF strategies need to be adopted and applied to achieve soil sustainability. In the soil–plant system, higher soil organic matter resulted in a higher percentage of macroaggregates that improve pores for aeration and water flow to sustain these soils.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11091465/s1, Table S1: Annual average weather data recorded at ICAR-IIFSR agrometeorology observatory during 2006–2017, data represent mean ± SD (average/annual), Kurtosis and Skewness test, Patents—NIL.

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