**Impact of Climate Resilient Agriculture on Soil Physical Properties of Samastipur District Soil of Bihar, India**

**Abstract**

Climate resilient agricultural (CRA) practices in overcoming barriers faced in agri-food system by farmers across the different villages of the Samastipur district of Bihar? In view of the increasing effects of climate change on global agri-food systems, this study investigates the obstacles that prevent farmers in Bihar from using CRATs. Two hundred fifty surface soil samples (0-15 cm) were collected from the villages of Chakpahad, HarpurBhindi, ChakoBhindi, Rampur Maheshpur, Rampur Morba, and KVK Virauli, representing ten selected agricultural systems. Ten treatments incorporating combinations of zero tillage, residue retention, and permanent bed systems were evaluated. Results showed that while bulk density remained largely unchanged, CRA treatments significantly improved available water content, aggregate size distribution, and mean weight diameter (MWD). Treatments T5 and T3 consistently enhanced soil structure and moisture retention across locations, with T5 exhibiting superior aggregate stability and reduced fine particle fractions. These findings highlight CRA’s potential to strengthen soil health and resilience under climate stress conditions in the Indo-Gangetic plains.

**Keywords:** *Climate Resilient Agriculture, Physical Properties, Soil Health*

**Introduction**

The performance of Indian agriculture is being significantly impacted by climate change and its unpredictability. Climate change brought on by long-term shifts in weather patterns puts agricultural output at risk due to increasing sea levels, higher rainfall unpredictability, and high and low temperature regimes that could degrade coastal freshwater supplies and raise the danger of flooding. Higher temperatures are likely to reduce yields of many crops; and encourage the explosion of weeds and pests. Even while certain parts of the world have seen improvements in food yields and other benefits, climate change is probably going to have a negative overall effect on agriculture. Since 1975, the global temperature has increased by 0.15 to 0.20°C every ten years (NASA, 2020), and by 2021, it is expected to have increased by 1.4 to 5.8°C (Arora *et al*., 2005). Climate resilient agriculture is a crucial prerequisite for sustainable development in the face of climate change, which includes adaptation and mitigation techniques as well as the efficient utilisation of biodiversity at all levels, including genes, species, and ecosystems. In Bihar, the concept of climate-resilient agriculture has evolved considerably due to the state’s exposure to climate change and the government’s proactive measures. Bihar’s diverse agro-climatic zones frequently experience climate-related issues, such as northern floods and southern droughts. To tackle these problems, the Bihar State Action Plan on Climate Change (BAPCC), developed in 2015, includes climate-resilient strategies adapted to local conditions. The BAPCC aims to transform agriculture into a robust and adaptable production system. This transformation involves promoting sustainable agricultural practices, developing crop varieties that can withstand climate stress, and implementing efficient water management techniques. Furthermore, the state has prioritized integrated pest management, soil health enhancement, and crop diversification to boost resilience against climate variability.To address the issues raised by climate change in agriculture, a multi-stakeholder coalition is implementing the Climate Resilient Agriculture program. The Bihar government, in particular the Department of Agriculture, is essential in developing policies and promoting the execution of CRA programs (Jat *et al.*, 2025).

Research and initiatives in Bihar emphasize the need to analyse soil health and chemical properties within the framework of climate-resilient agriculture (CRA) practices. This study focuses on evaluating the chemical properties of soil, along with the overall soil health index, which includes soil organic carbon, under various CRA practices. Gaining insights into these aspects will enable Bihar to enhance and fine-tune its agricultural strategies, thereby improving resilience and sustainability in response to climate change.

**Materials and Methods**

The research was conducted in the Samastipur district, located in the Indo-Gangetic plains of Bihar, India. The region is characterised by calcareous soils, a subtropical climate, and a cropping system dominated by rice-wheat rotations. The survey and assessment concentrated predominantly on the eastern region of the Indo-Gangetic Plain, with particular emphasis on the state of Bihar in India. From village*viz*. Chakpahad, HarpurBhindi, ChakoBhindi, Rampur Maheshpur, Rampur Morbaand KVK Virauli250 surface soil samples (0-15 cm) were collected from selected 10 cropping systems (T1 to T10)T1: Transplanted rice-conventional tillage wheat-fallow, T2: Direct seeded rice-zero tillage wheat – zero tillage green gram, T3: Transplanted rice – zero tillage wheat – zero tillage green gram, T4: Direct seeded rice – zero tillage lentil – zero tillage green gram, T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, T6: Direct seeded rice – potato – zero tillage green gram, T7: Direct seeded rice -raised bed planting maize – zero tillage green gram, T8: Raised bed planting maize – potato- zero tillage green gram, T9: Raised bed planting maize – zero tillage wheat – zero tillage green gram, T10: Raised bed planting maize – zero tillage lentil – zero tillage green gram, across six villages, with five samples collected from each village, covering Samastipur (a region with calcareous soil),sampling done randomly by using the standard sapling method. The collected soil samples were dried in the shade, grinding with a wooden pestle and mortar, sieved twice, and stored in polythene bags for chemical analysis. The 2 mm sieved materials were ground and put through a 0.2 mm sieve for organic carbon analysis. As indicated by Bouyoucos (1962), particle size analysis was done using the Hydrometer method with sodium hexametaphosphate as a dispersion agent. These samples will be analysed for their physical properties, including bulk density (Black, 1965), soil texture (Piper, 1966), wet aggregate stability (Moebius *et al.*, 2007) and available water content (Cassel and Nielsen, 1986).

**Result and Discussion**

The impact of various Climate Resilient Agriculture (CRA) practices on the physical properties of soil in Chakpahad village was significant across multiple parameters shown in Table 1. Bulk density values remained constant among treatments, ranging from 1.41 to 1.42 g cm-3, suggesting no statistical variation in soil compaction due to CRA interventions.Available water content showed notable variation. The highest value was recorded under treatment T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (34.53%), followed closely by T6 (32.62%) and T4 (32.13%), indicating the positive influence of permanent bed and zero tillage systems with residue retention on soil moisture conservation. In contrast, conventional practices under treatment T10 resulted in the lowest available water (25.41%).Aggregate size distribution also reflected treatment-specific differences. Treatment T3: Transplanted rice – zero tillage wheat – zero tillage green gram exhibited the greatest proportion of large aggregates (AG2), with a value of 14.05 g/100g, whereas T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram closely followed with 13.63 g/100g. Medium-sized aggregates (AG253) were most prevalent in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (49.11 g/100g), highlighting improved soil structural integrity, while T7 recorded the lowest value in this category. The finest aggregates (AG53) were most abundant in T10 (44.91 g/100g), suggesting higher fragmentation and possibly reduced aggregation under conventional tillage.Mean Weight Diameter (MWD), a key indicator of soil aggregate stability, ranged from 0.68 mm in T10 to 0.79 mm in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram. Higher MWD values were observed in treatments T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, T3: Transplanted rice – zero tillage wheat – zero tillage green gram, and T9, signifying enhanced structural stability associated with CRA practices involving residue retention and reduced soil disturbance. These findings support previous studies showing that residue management and minimal tillage improve soil moisture retention by lowering evaporation and enhancing penetration. Increased organic matter and better soil structure, which boost the soil's ability to retain water, are probably the causes of these treatments higher water availability (Jat *et al.*, 2025).

**Table 1.** Impact of CRA on the physical properties of Chakpahadvillage soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3)** | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD (mm)** |
| **>2 mm**  **(AG2)** | **2-0.053 mm (AG253)** | **<0.053 mm (AG53)** |
| T1 | 1.42a | 25.49g | 13.19ab | 44.75cb | 42.06cab | 0.73cadb |
| T2 | 1.42a | 30.31dc | 11.75cb | 46.60cab | 41.65cab | 0.72cdb |
| T3 | 1.42a | 27.60fe | 14.05a | 47.24ab | 38.71cd | 0.78ab |
| T4 | 1.42a | 32.13bc | 11.93cab | 44.27cb | 43.80ab | 0.71cd |
| T5 | 1.42a | 34.53a | 13.63ab | 49.11a | 37.27d | 0.79a |
| T6 | 1.42a | 32.62b | 12.52cab | 44.96cb | 42.52cab | 0.72cdb |
| T7 | 1.41a | 28.47de | 11.85cab | 43.96c | 44.19ab | 0.70cd |
| T8 | 1.42a | 26.28gf | 12.29cab | 44.92cb | 42.79cab | 0.72cdb |
| T9 | 1.42a | 27.24gfe | 13.04cab | 47.24ab | 39.72cdb | 0.76cab |
| T10 | 1.42a | 25.41g | 10.84c | 44.21c | 44.91a | 0.68d |

In Harpur Bhindi, the assessment of soil physical properties under treatments T1 to T10are shown in Table 2, with varying effects on bulk density, water availability, and aggregate distribution. BD values remained consistent across treatments, ranging from 1.41 g cm-3 to 1.43 g cm-3, with T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram recording the highest BD, possibly indicating slightly greater compaction compared to others, while T4 had the lowest, reflecting better soil porosity. Available Water Content exhibited a broad range from 26.74 g 100g-1 in T10 to 37.66 g 100g-1 in T7, marking T7 as the most effective in enhancing soil water retention, which is a critical factor for crop sustainability during moisture stress periods. In terms of aggregate size distribution, the fraction of macro-aggregates (>2 mm, AG2) was highest in T3 (14.42 g 100g-1), followed closely by T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, indicating improved soil structural stability and organic matter integration in these treatments. T10 showed the lowest AG2 content (11.15 g 100g-1), suggesting weaker aggregate formation. The medium-sized aggregate fraction (2–0.053 mm, AG253) was most abundant in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (50.28 g 100g-1), supporting its classification as the most structurally robust soil among treatments, while T4 and T7 exhibited lower values, potentially impacting soil aeration and permeability. Fine particles (<0.053 mm, AG53) were highest in T10 (43.53 g 100g-1), which may reflect a greater presence of dispersed particles and reduced aggregate stability, while T5 again showed the lowest value (35.75 g 100g-1), further confirming its favourable structural attributes. Mean Weight Diameter (MWD), a key indicator of aggregate stability, ranged from 0.70 mm in T10 to 0.81 mm in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, with T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram significantly outperforming others, highlighting its superior resistance to disintegration under water stress or tillage. T3: Transplanted rice – zero tillage wheat – zero tillage green gram also recorded a high MWD (0.80 mm), reinforcing its effectiveness in enhancing aggregate resilience.Root exudates contained a wide range of organic and inorganic materials, which made soil microaggregates more stable in the soil (Rougier, 1981). Plant roots also make polysaccharides, which help hold particles together and make soil clump together better in cropped plots than in fallow ones (Verma *et al.*, 2021)

**Table 2.** Impact of CRA on the physical properties of Harpur Bhindi village soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3)** | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD** |
| **>2 mm**  **(AG2)** | **2-0.053 mm (AG253)** | **<0.053 mm (AG53)** |
| T1 | 1.42ab | 27.81cb | 13.56ab | 45.96cb | 40.48cab | 0.75cadb |
| T2 | 1.41abab | 29.89cab | 12.02cb | 47.73cab | 40.26cab | 0.74cdb |
| T3 | 1.41ab | 30.71cab | 14.42a | 48.36ab | 37.21cd | 0.80ab |
| T4 | 1.41b | 33.07a | 12.25cab | 45.25c | 42.51ab | 0.72cd |
| T5 | 1.43a | 32.18a | 13.98ab | 50.28a | 35.75d | 0.81a |
| T6 | 1.41ab | 30.00cab | 12.81cab | 46.02cb | 41.17cab | 0.74cdb |
| T7 | 1.42ab | 37.66cb | 12.13cab | 45.22c | 42.65ab | 0.72cd |
| T8 | 1.41ab | 27.62cb | 12.59cab | 46.16cb | 41.24cab | 0.74cdb |
| T9 | 1.41ab | 31.11ab | 13.32cab | 48.51ab | 38.17cdb | 0.77cab |
| T10 | 1.41ab | 26.74c | 11.15c | 45.31c | 43.53a | 0.70d |

In ChakoBhindi, the physical characteristics of the soil across treatments T1 to T10are shown in Table 3, revealing considerable variation in water retention properties, despite the bulk density remaining uniform at around 1.41–1.42 g cm-3 across all treatments, indicating minimal differences in soil compaction or porosity. Available Water content varied significantly, with the highest value observed in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (34.53 g 100g-1), followed by T6 and T3: Transplanted rice – zero tillage wheat – zero tillage green gram, reflecting a greater capacity to retain moisture under these treatments, while T10 and T1 exhibited the lowest water availability, potentially indicating reduced plant-accessible moisture. Aggregate size distribution data revealed that the proportion of large aggregates (>2 mm, AG2) was highest in T3: Transplanted rice – zero tillage wheat – zero tillage green gram (14.64 g 100g-1), suggesting improved soil structure and organic matter aggregation, with T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram also demonstrating a high value in this size class, whereas T10 recorded the lowest AG2 proportion. Medium-sized aggregates (2–0.053 mm, AG253), vital for maintaining soil tilth and root penetration, were highest in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram(50.37 g 100g-1), indicating excellent structural development, while T7 had the lowest proportion, hinting at less desirable physical conditions. The fine fraction (<0.053 mm, AG53) was lowest in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (35.61 g 100g-1), again supporting its structural stability, while T10 recorded the highest proportion (43.47 g 100g-1), suggesting a tendency toward finer-textured, less aggregated soils. Mean Weight Diameter (MWD), a key indicator of aggregate stability, was greatest in T3: Transplanted rice – zero tillage wheat – zero tillage green gram (0.81 mm) and T5 (0.81 mm), underscoring these treatments as superior in promoting stable aggregates resistant to disintegration and erosion, whereas T10 had the lowest MWD (0.70 mm), reflecting weaker soil structural integrity.

**Table 3.** Impact of CRA on the physical properties of ChakoBhindi village soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3**) | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD** |
| **>2mm (AG2)** | **2-0.053mm (AG253)** | **<0.053mm (AG53)** |
| T1 | 1.41a | 25.52f | 13.73ab | 46.76cdb | 39.52cab | 0.76cab |
| T2 | 1.41a | 29.23ecd | 12.18cb | 48.31cab | 39.51cab | 0.75cab |
| T3 | 1.41a | 31.26cb | 14.64a | 49.19ab | 36.17c | 0.81a |
| T4 | 1.41a | 29.43cd | 12.42cab | 46.09cd | 41.49ab | 0.73cb |
| T5 | 1.41a | 34.53a | 14.01ab | 50.37a | 35.61c | 0.81a |
| T6 | 1.42a | 32.62ab | 12.80cab | 46.07cd | 41.13ab | 0.74cb |
| T7 | 1.42a | 28.47ecfd | 12.19cb | 45.01d | 42.80ab | 0.72cb |
| T8 | 1.42a | 26.28ef | 12.57cab | 46.15cd | 41.27ab | 0.74cb |
| T9 | 1.41a | 27.24efd | 13.39cab | 48.29cab | 38.32cb | 0.77ab |
| T10 | 1.41a | 25.41f | 11.16c | 35.36cd | 43.47a | 0.70c |

In Rampur Maheshpur, the physical properties of soil under different treatments (T1 to T10) are shown in Table 4, revealing key differences in soil structure and moisture retention, although bulk density values remained uniform at approximately 1.41–1.42 g cm-3 across all treatments, indicating similar soil compaction levels. Available Water Content (AWC) showed noteworthy variation, with the majority of treatments ranging from 25.50 to 34.53 g 100g-1; however, T10 presented an outlier with an anomalously high AWC value of 75.31 g 100g-1, which may suggest a data entry error or an unusually high organic matter or porosity condition that warrants further verification. Aggregate size distribution further illustrated treatment-induced variation, particularly in the >2 mm (AG2) fraction, which was highest in T10 (17.12 g 100g-1) and T3: Transplanted rice – zero tillage wheat – zero tillage green gram and T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (13.68 and 13.30 g 100g-1, respectively), reflecting improved macroaggregate formation. The medium aggregate class (2–0.053 mm, AG253) peaked in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (47.83 g 100g-1), with T3: Transplanted rice – zero tillage wheat – zero tillage green gram and T9 also registering high values, implying greater soil stability and improved structure in these treatments. The fine particle fraction (<0.053 mm, AG53) was most concentrated in T10 (37.21 g 100g-1), while T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram had the lowest value (38.87 g 100g-1), both of which deviate slightly from the typical pattern due to T10 unusual figures. Mean Weight Diameter (MWD), a metric for aggregate stability, ranged from 0.68 mm in T7 to a maximum of 0.77 mm in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, with T3: Transplanted rice – zero tillage wheat – zero tillage green gram (0.76 mm) and T9 (0.74 mm) closely following, suggesting that these treatments promoted better resistance to aggregate breakdown and improved soil structure. Taken together, treatments T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram, T3: Transplanted rice – zero tillage wheat – zero tillage green gram, and T9 emerged as the most favourable in enhancing physical soil quality in this village, while T10 extreme values invite closer scrutiny for accuracy or atypical soil conditions.

**Table 4.**Impact of CRA on the physical properties of Rampur Maheshpurvillage soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3)** | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD** |
| **>2mm (AG2)** | **2-0.053mm (AG253)** | **<0.053mm (AG53)** |
| T1 | 1.42a | 25.50a | 12.88a | 43.69cb | 43.42a | 0.72a |
| T2 | 1.42ab | 30.31a | 11.46a | 45.40cab | 43.14a | 0.71a |
| T3 | 1.42ab | 27.60a | 13.68a | 46.18ab | 40.15a | 0.76a |
| T4 | 1.41b | 32.13a | 11.59a | 43.02c | 45.39a | 0.69a |
| T5 | 1.42ab | 34.53a | 13.30a | 47.83a | 38.87a | 0.77a |
| T6 | 1.42ab | 32.62a | 12.22a | 43.98cb | 43.79a | 0.71a |
| T7 | 1.42ab | 28.47a | 11.57a | 42.92c | 45.52a | 0.68a |
| T8 | 1.41ab | 26.28a | 12.03a | 43.79cb | 44.15a | 0.70a |
| T9 | 1.42ab | 27.24a | 12.68a | 46.09ab | 41.23a | 0.74a |
| T10 | 1.41ab | 75.31a | 17.12a | 43.68cb | 37.21a | 53.86a |

In Rampur Morba, the analysis of soil physical properties across treatments T1 to T10 are shown in Table 5, revealed subtle differences in bulk density (BD), which remained relatively uniform around 1.41–1.43 g cm-3, though T2 showed a slightly higher BD (1.43 g cm-3), possibly indicating marginally denser soil compaction, while T5 and T10 had the lowest BD (1.41 g cm-3), potentially favouring better aeration and root penetration. Available Water Content (AWC) varied noticeably, with T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram recording the highest value at 34.55 g 100g-1, followed by T6 and T4, reflecting enhanced water retention under these treatments, whereas the lowest AWC was observed in T10 (25.43 g 100g-1), indicating limited soil moisture availability.In terms of aggregate size distribution, the fraction of macroaggregates (>2 mm, AG2) was highest in T3: Transplanted rice – zero tillage wheat – zero tillage green gram (13.80 g 100g-1), closely followed by T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram and T1, suggesting better soil structural development and resistance to erosion in these treatments, while the lowest AG2 content was recorded in T10 (10.73 g 100g-1), implying a weaker aggregation pattern. The medium-sized aggregate fraction (2–0.053 mm, AG253), which is crucial for plant growth and water dynamics, peaked in T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (47.81 g 100g-1) and T3 (46.17 g 100g-1), highlighting their superior structural quality, whereas treatments like T4 and T7 exhibited lower values, potentially limiting soil aeration and water flow. The fine fraction (<0.053 mm, AG53) was most abundant in T10 (45.63 g 100g-1) and T7 (45.58 g 100g-1), indicating a greater tendency toward finer soil particles that may hinder infiltration and encourage surface crusting, while T5 recorded the lowest fine fraction (38.89 g 100g-1), aligning with its strong aggregate formation. Mean Weight Diameter (MWD), a direct measure of aggregate stability, ranged from 0.68 mm in T10 to 0.77 mm in T5, reaffirming T5 as the treatment with the most stable and cohesive soil aggregates, whereas lower MWD values in T10, T7, and T4 reflect comparatively fragile soil structure. Collectively, these findings position T5 and T3: Transplanted rice – zero tillage wheat – zero tillage green gram as the most effective treatments in improving the physical quality of soil in Rampur Morba, through a combination of superior water retention, aggregate structure, and stability.

**Table 5.** Impact of CRA on the physical properties of Rampur Marbavillage soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3)** | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD** |
| **>2mm (AG2)** | **2-0.053 mm (AG253)** | **<0.053mm (AG53)** |
| T1 | 1.42ab | 25.80gf | 13.29ab | 43.99cb | 42.71cab | 0.73ab |
| T2 | 1.43a | 30.33cd | 11.47cb | 45.50cab | 43.03cab | 0.71ab |
| T3 | 1.42ab | 27.62ef | 13.80a | 46.17ab | 40.03cb | 0.76a |
| T4 | 1.42ab | 32.15cb | 11.65cab | 43.07cb | 45.28a | 0.69b |
| T5 | 1.41b | 34.55a | 13.30ab | 47.81a | 38.89c | 0.77a |
| T6 | 1.42ab | 32.64ab | 12.22cab | 43.87cb | 43.90ab | 0.71ab |
| T7 | 1.41ab | 28.49ed | 11.60cb | 42.82c | 45.58a | 0.68b |
| T8 | 1.42ab | 26.30gf | 11.99cab | 43.89cb | 44.12ab | 0.70b |
| T9 | 1.42ab | 27.26gef | 12.71cab | 46.04ab | 41.26cab | 0.74ab |
| T10 | 1.41b | 25.43g | 10.73c | 43.64cb | 45.63a | 0.68b |

In KVK Virauli, the soil physical properties under treatments T1 through T10 exhibited significant variations that reflect the impact of different management practices on soil structure and moisture dynamics. Bulk density (BD) remained relatively consistent across treatments, with values between 1.40 and 1.42 g cm-1, where T2 recorded a slightly lower BD, suggesting improved soil porosity and potential root penetration advantages. Available Water Content (AWC) varied more prominently, ranging from 25.35 g 100g-1 in T10: Raised bed planting maize – zero tillage lentil – zero tillage green gram to a maximum of 34.47 g 100g-1 in T5, marking T5 as the most effective in enhancing soil moisture retention, which could be beneficial for drought resilience. Aggregate size distribution further distinguished the treatments, with the proportion of large aggregates (>2 mm, AG2) highest in T3: Transplanted rice – zero tillage wheat – zero tillage green gram (14.03 g 100g-1) and T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram (13.62 g 100g-1), indicating superior macro-aggregate formation and potential for erosion resistance, while T10: Raised bed planting maize – zero tillage lentil – zero tillage green gram had the lowest AG2 value, suggesting relatively poorer structural development. In the medium-sized aggregate class (2–0.053 mm, AG253), T5 again led with 49.07 g 100g-1, followed closely by T3: Transplanted rice – zero tillage wheat – zero tillage green gram and T9, supporting the conclusion that these treatments foster more robust aggregate structures. The fine aggregate fraction (<0.053 mm, AG53) was highest in T10: Raised bed planting maize – zero tillage lentil – zero tillage green gram and T4, which may restrict soil permeability and aeration due to a finer texture, whereas T5: Direct seeded rice- raised bed planting mustard – zero tillage green gram recorded the lowest, reinforcing its stronger structural profile. Mean Weight Diameter (MWD), an integrative indicator of aggregate stability, ranged from 0.696 mm in T10: Raised bed planting maize – zero tillage lentil – zero tillage green gramto a maximum of 0.79 mm in T5, with T3: Transplanted rice – zero tillage wheat – zero tillage green gram and T9 also performing well, confirming the structural stability and resilience of these treatments under stress conditions such as water erosion or compaction. Collectively, treatments T5 and T3: Transplanted rice – zero tillage wheat – zero tillage green gramemerged as the most favourable in improving physical soil quality in KVK Virauli, through enhanced water-holding capacity, stable aggregates, and favourable textural balance.

**Table 6.** Impact of CRA on the physical properties of KVK Viraulivillage soil.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Bulk Density (g cm-3)** | **Available Water (%)** | **Weight of Aggregate (g 100g-1)**  **Aggregate size distribution** | | | **MWD** |
| **>2mm (AG2)** | **2-0.053mm (AG253)** | **<0.053mm (AG53)** |
| T1 | 1.42a | 25.43g | 13.23cab | 44.84cb | 41.93ab | 0.74cab |
| T2 | 1.40b | 30.25dc | 11.70cb | 46.54cab | 41.76abg | 0.72cab |
| T3 | 1.42ab | 27.54fe | 14.03a | 47.27ab | 38.71cb | 0.78ab |
| T4 | 1.41ab | 32.07bc | 11.91cab | 44.28cb | 43.81a | 0.71c |
| T5 | 1.41ab | 34.47a | 13.62ab | 49.07a | 37.31c | 0.79a |
| T6 | 1.41ab | 32.55b | 12.53cab | 44.97cb | 42.50ab | 0.72cab |
| T7 | 1.41ab | 28.41de | 11.84cab | 44.01c | 44.14a | 0.70c |
| T8 | 1.41ab | 26.22gf | 12.25cab | 45.01cb | 42.75ab | 0.72cb |
| T9 | 1.41ab | 27.17gfe | 12.95cab | 47.26ab | 39.80cab | 0.75cab |
| T10 | 1.42ab | 25.35g | 11.09c | 45.09cb | 43.82a | 0.70c |

**Conclusion**

The study clearly demonstrates that Climate Resilient Agriculture practices significantly enhance soil physical properties in the Samastipur district of Bihar. Treatments involving zero tillage, residue retention, and permanent bed systems particularly T5: Direct seeded rice- raised bed planting mustard – zero tillage green gramand T3: Transplanted rice – zero tillage wheat – zero tillage green gram, consistently improved available water content, aggregate size distribution, and mean weight diameter (MWD) across all three villages. These improvements reflect better soil structure, increased moisture retention, and enhanced aggregate stability, which are critical for sustaining crop productivity under climate stress. Although bulk density remained relatively unchanged, the overall enhancement in soil quality under CRA treatments supports their broader adoption in the Indo-Gangetic plains. The findings reinforce the role of CRA as a viable strategy for promoting sustainable agriculture and improving soil resilience in vulnerable agro-ecosystems.

Disclaimer (Artificial intelligence)

I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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