Review Article

Assessing the Influence of Soil Physical Properties on the Puddling Quality: A Comprehensive Review

ABSTRACT

Puddling is a crucial step in rice cultivation, extensively practiced by farmers in Asia for its role in softening soil, aiding in transplanting, and enhancing water and nutrient management. However, the alteration of soil properties by puddling raises concerns about its long-term sustainability. This comprehensive review systematically examines the impact of puddling on soil parameters such as soil texture, bulk density, penetration resistance, hydraulic conductivity, puddling index, and percolation rate. By synthesizing existing literature, the review aims to inform sustainable agricultural practices and effective soil management strategies amidst escalating global concerns. The complexities of puddling's influence on soil structure underscore the need to consider variables like soil texture and aggregate stability. Sustainable practices such as organic manure application offer potential solutions to address puddling-induced compaction, thereby enhancing soil quality and rice production efficiency. Optimizing tillage methods and improving hydraulic conductivity are essential components of effective soil management strategies for sustainable rice cultivation. Additionally, assessing puddling quality through indices like the puddling index and optimizing percolation rates are vital steps toward improving water management and overall productivity in rice farming.

Key Words: Hydraulic Conductivity, Penetration Resistance, Percolation rate, Puddling, Puddling Index, Soil Bulk density, Soil texture

1. Introduction:

Rice (*Oryza sativa*) stands as a cornerstone of sustenance in Asian countries, serving as a staple food source for millions, particularly small-scale farmers cultivating vast expanses of land. The Government of India estimates the rice production for the fiscal year 2022-23 to reach a substantial 1308.37 lakh tonnes. Integral to the cultivation of rice is a series of meticulous operations, from land preparation to harvest, each playing a crucial role in creating an optimal environment for crop growth. Among these operations, puddling emerges as a significant step in the cultivation process, involving the churning of soil with water to prepare it for cultivation. Puddling offers advantages such as facilitating transplanting, improving water conservation, reducing soil permeability, and enhancing nutrient availability.Puddling is widely adopted in rice farming for various purposes (Adachi and Sakaki, 1999; Kaneki, 2003). It serves to soften the soil in the plough layer, aiding in transplanting or direct seeding, creating a smooth soil surface, maintaining consistent flood water depth for efficient water control, reducing weed growth, promoting the integration of fertilizer and soil in the plough layer, and lowering the percolation rate

The process of puddling contributes to the formation of a compacted soil layer in rice fields, impacting water infiltration and drainage. This compaction, while reducing water permeability, enhances water retention in the root zone, a critical factor for the initial stages of rice growth, especially during germination and early seedling development. Given the adaptability of rice plants to anaerobic environments, puddling ensures the saturation of soil with water, creating conditions conducive to early growth. However, the sustainability of puddling practices has come under scrutiny due to potential long-term repercussions on essential soil properties.

Effective soil management is pivotal for sustainable agriculture and environmental health. Puddling, a prevalent practice in rice cultivation, has garnered attention due to its implications for various soil characteristics. While the primary objective of puddling is to enhance water retention and suppress weed growth, questions about its impact on crucial soil properties have surfaced. This comprehensive review undertakes a detailed exploration of the influence of puddling on a range of soil properties. These include, but are not limited to, soil texture, bulk density, penetration resistance, hydraulic conductivity, puddling index, and percolation rate. Through an exhaustive examination of these parameters, we aim to offer a nuanced comprehension of the intricate interactions between puddling practices and soil health.

As global concerns regarding sustainable agriculture and environmental impact continue to escalate, a meticulous analysis of how puddling affects key soil properties becomes imperative. This review adopts a systematic approach, synthesizing information from existing literature and research findings to explain the complex relationships between puddling practices and various soil properties. By acquiring a profound understanding, our objective is to contribute insights that inform the development of sustainable agricultural practices and effective soil management strategies. This endeavor holds promise in addressing the evolving challenges in rice cultivation while promoting environmentally responsible approaches for future agricultural endeavors.

Fig.1 : Puddling on a Wetland (Verma and Dewangan, 2006)

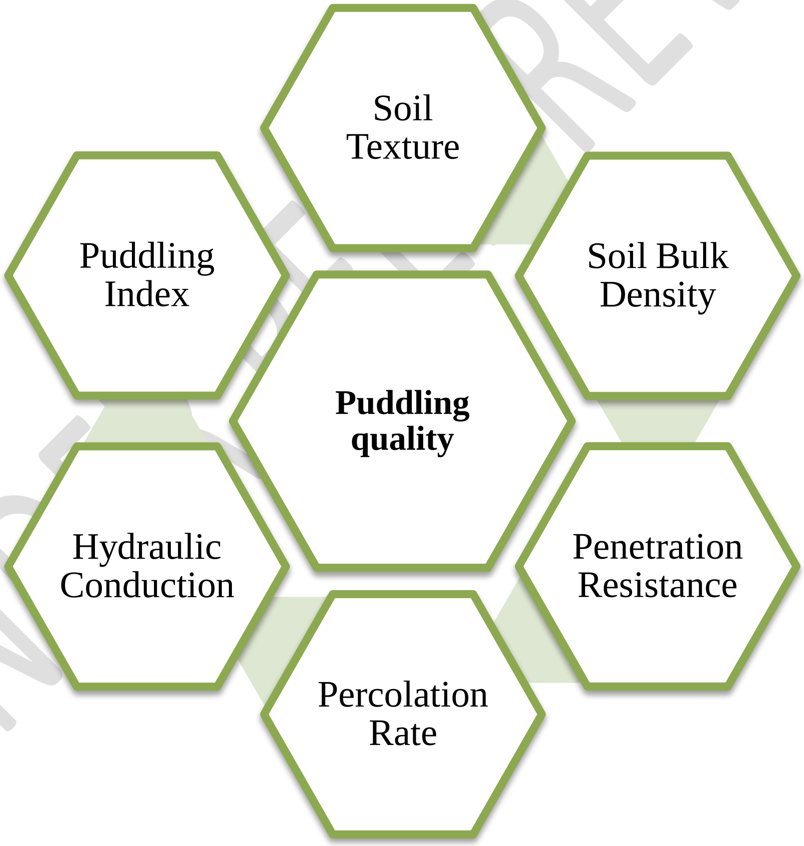

Fig.2 :Parameters influence the puddling quality

2. Puddler

The Cage Wheels, utilized with both two-wheel and four-wheel tractors, steel cage wheels enhance soil puddling and facilitate weed burial by operating under conditions of high wheel slip. This method can be complemented by the attachment of a rotavator or the trailing of a leveling board to further disturb the soil and cover weeds. The Hydro-tillers, machines employ a powered rotor to puddle the soil while also burying weeds and residues. Hydro-tillers, which are propelled by an engine-driven rotor, feature a platform equipped with airtight floats, allowing them to operate exclusively in flooded fields. Transportation of hydro tillers to and from fields can present challenges; however, some models are equipped with wheels attached outside the rotor to facilitate movement.The pulverizing roller (fig.3)serves as an accessory for commercially accessible tine cultivators, offering versatility for both puddling and preparing dry seed beds. Comprising six pulverizing members crafted from MS steel flats, these members traverse through slots within star wheels. The attachment of the roller to the cultivator is facilitated by two links equipped with bearing housing on one end and tensile springs on the other.A rotavator is designed to efficiently prepare seedbeds in a single operation, accommodating both dry and wetland conditions. Its components typically include a frame, a rotary shaft equipped with blades, and a power transmission system connecting the gearbox to the shaft. The Tractor-Mounted Puddlers, similar to a rotavator but distinct in their design, tractor-mounted puddlers are equipped with less robust structures, featuring smaller drums and shoes. They tend to be wider than standard rotavators and can be operated in both wet and dry soil conditions, although they are most effective in fields with standing water. These puddlers are designed to leave the field surface level and yield optimal results when guided by laser technology (Chhina, 2015).

Fig.3: Pulverizing roller (Chhina, 2015)

Fig.4 : Rotavator (Chhina, 2015)

3. SOIL PROPERTIES

3.1. Soil Texture

The influence of puddling over the surface of soil structure relies on factors such as the texture of the soil and aggregate stability. Aggregate stability, shaped along the elements like clay fraction quantity and type, organic matter, hydrous oxides, interparticle bond formation, and soil solution electrolyte concentration, plays a crucial role. While puddling generally has an adverse impact on soil structure for upland crops, it is noteworthy that rice cultivation may, in certain instances, improve subsoil structure. Over extended periods of repeated puddling, soils undergo notable structural transformations, with the specific changes varying based on soil texture. Soils that undergo puddling demonstrate shrinkage and form weakened structures, which are marked by decreased amounts of water-stable aggregates when they dry (Greenland, 1985). In an assessment conducted on changes in soil texture within the puddle layer resulting from soil particle redistribution during settling post-puddling. The evaluation was based on collected samples, and the particle size distribution within the puddled layer at different depths was determined using the pipette and sieving method(Kirchhof and So, 2005). The bulk density may increase over time, even in submerged soil, due to particle settling. Soil particle settling and consolidation can occur through the deflocculation of dispersed clay, influenced by factors such as soil texture, type of clay, and the strong concentrations of the solution of the soil (Sharma and Datta, 1986). The conservation of soil during agricultural machinery operations is primarily subjected to organic content, texture of the soil, and soil-water content (Mosaddeghi*et al.*, 2000; Andrade-Sánchez *et al.*, 2007). The studies statethat variations in soil texture induced by tillage practices may also impact soil moisture retention properties(Lal, 1986).

The impact of puddling on the water transmission characteristics of soil is contingent upon various factors, including soil texture, type of clay, stability of aggregates in water, intense of puddling, and closeness of the water table and the surface of the soil (Sharma and Datta, 1985). The infiltration rate is influenced by soil texture and structure, with higher rates associated with larger soil particles and more dispersed structures(Mufti and Khan, 1995). The water percolation rate can decrease by about 92%, relying on parameters such as soil texture, puddling depth, and intensity (Sandhu and Singh, 2001). The effects on roots may vary based on soil texture and bulk density. Pore-size distribution, influenced by texture, plays a significant role in influencing root growth and the distribution of total porosity (Kar *et al.*, 1979). In soils with lower water potentials (more negative), puddled soils consistently exhibit higher water retention capacity compared to non-puddled soils. This variation is dependent on soil texture and initial aggregation (Bodman and Day, 1943; Buehrer and Rose, 1943; Campbell, 1952; Jamison, 1953; Croney and Coleman, 1954; Warkentin, 1962; Taylor, 1972; Yun-sheng, 1983).

3.2. Bulk Density

Soil bulk density serves as a crucial indicator for monitoring alterations in soil structure and water retention capacity (Arshad *et al.*,1999).Bulk density is considered a vital soil physical parameter widely employed for assessing soil compactness. Its values are subject to fluctuations based on both management practices and inherent soil attributes. Due to its reliance on inherent soil properties, the utility of bulk density measurements is constrained when evaluating the impact of soil management on compactness, particularly when comparing soils with diverse inherent characteristics (Kalita *et al.*, 2020). No-till practices result in higher bulk density at the surface compared to tilled soil (Azooz*et al.*,1996).) It is observed that thebulk density was higher at the 0–7.5 cm soil depth under no-till compared to conventional tillage(Kumar *et al.*, 2002). The reduction in bulk density through puddling aligns with findings from earlier researchers. Puddling a high bulk density soil was observed to lower bulk density by fostering an open soil structure(Bhagat *et al.*1994).

The puddling reduces the bulk density of moisture-less and dense lowland soils next to re-suspending soil particles that are packed together(Bodman and Rubin,1948). However, in soils with a well-aggregated, open structure, puddling tends to increase bulk density. The alteration in bulk density due to puddling relies on the status of soil initialaggregation. Transitioning from awell-aggregated open structure to a closely packed parallel-oriented structure increases bulk density, and vice versa(Aylmore and Quirk, 1962). The bulk density of the surface layer of soil under conventional tillage was higher than in soil from zero-till plots (Chang *et al.*,1992). This difference may be attributed to the higher saturation percent observed in zero-till and minimum tillage compared to conventional tillage.The decreased bulk density of no-till plots is attributed to elevated organic matter content and root concentration (Rodriguez and Lal, 1985).

The puddling led to a 30% reduction in the bulk density of two sets of soils in the upper 0.1m layer(Sharma and Datta, 1985). However, variation in bulk density between puddled and non-puddled soil diminished over the period. Additionally, puddling notably reduces bulk density in the top layer of soil (0.2m).Mohanty (2004) found that in puddled soil, soil bulk density significantly increased from transplanting to harvest. Puddling, particularly in layers 0 - 50mm, 50 - 100mm, and 100 -150mm, led to a notable reduction in bulk density (Mg m^{-3}), with a more pronounced decrease associated with higher puddling intensity.Sharma and Datta (1986) observed that puddling induces a notable decline in the bulk density of the surface layer of lowland clay from 0.83 to 0.53 Mgm^{-3} and clay loam from 1.16 to 0.81 Mgm^{-3}. This reduction is attributed to the initial breakdown of soil aggregates, resulting in the loss of inter-aggregate transmission pores. Additionally, there is an observed rise in inter-domain pores and inter-micro aggregates. The study underscores the impact of puddling on soil structure and provides insight into the mechanisms contributing to the observed changes in bulk density.Asenso *et al.*(2022) experiment revealed a significant decrease in soil bulk density, particularly at a depth of 30 cm, when employing moldboard ploughing in conjunction with direct seeding.The soil bulk density values, ranging from 1.6 - 1.8 cm^{-3} at a depth of 20 - 25 cm, contrasted with 1.4 - 1.5 g cm^{-3}at the surface layer (0 to 12 cm), suggesting the presence of a plough pan in these soils (Akhtar and Qureshi, 1999).But Mathew *et al.* (2012) state that the Surface of soil in no-till and conventional-till handling exhibited lesser bulk density than the sub-surface of the soil, with no serious variation observed between the two methods of tillage.The experiment of Dewanti and Mandang (2022) also gives a notable reduction in bulk density after the puddling. The initial dry bulk density of the mud layer with stage-1 puddle method treatment was 0.87 g cm^{-3}, reducing post-tillage to 0.71 g cm^{-3}. Similarly, the mud layer treated with the stage-2 puddling method exhibited an initial density of 0.98 g cm^{-3}, decreasing post-tillage to 0.86 g cm^{-3}.

In a study, it was observed that both the type of puddler and the intensity of puddling exerted significant influences on bulk density hydraulic conductivity. The findings indicated that hydraulic conductivity exhibited a decreasing rate at higher soil bulk densities. Puddling was found to elevate the bulk density of the soil, consequently leading to a reduction in hydraulic conductivity(Behera 2009). These observations underscore the interconnected relationship between puddling practices, bulk density changes, and hydraulic conductivity in soil.Mousavi(2009) highlighted the significance of puddling intensity on soil bulk density, indicating a notable impact of varying puddling levels on this soil property.

A study assessed the bulk density of puddled soil at 30 and 60 Days After Puddling (DAP) in two experiments. Puddled soil consistently exhibited higher bulk density compared to unpuddled soil across all treatments. Increasing puddling intensity, particularly with three passes, significantly increased bulk density for the rotary puddler and showed a non-significant increase for the peg-type puddler and cultivator.The study also noted a correlation between the dispersion of soil particles and bulk density, with higher puddling indices corresponding to increased bulk density. Although there was a noteworthy increase in bulk density was observed only with the rotary puddler, possibly due to its higher puddling index. Bulk density exhibited an increase over time, attributed to soil shrinkage at lower moisture content. Notably, the treatment involving the rotary puddler with three passes significantly reduced both bulk density and hydraulic conductivity, yet resulted in reduced root growth and subsequently lower yields compared to other treatments(Behera *et al.* 2007).In a field experiment, there was a reduction in the bulk density in a clay loam (1.16 - 0.81 tm$^{-3)}$.The observed lower rice yields in dense soils are attributed to potential seedling root injuries during transplanting and the hindrance of root growth by the strong soil structure (Sharma and Datta, 1985).The study also highlights a negative correlation between bulk density, shear strength, and the growth and grain yield of transplanted rice. This underscores the importance of soil physical properties in influencing rice productivity, emphasizing the need for soil management practices that mitigate soil density and enhance root development for improved crop yields.

There was a negative correlation between Root-Length Density (RLD) at the 0- to 0.10m depth during harvest and soil bulk density at transplanting(Sharma *et al.* 1998).In the experiment by Mohanty (2004), it was analyzed that low-puddled soil exhibited higher bulk density, possibly attributed to a faster rate of settling.According to Akhtar *et al.* (2008), soil bulk density serves as a straightforward indicator of soil compaction. Any observed rise in bulk density at specific depths with varying tillage practices is considered direct evidence of soil compaction.Also, according to Alongo and Kombele, (2009), bulk density functions as an indicator of soil compaction and provides insight into the quantity of void space within the soil.Soil moisture, soil type, texture, and bulk density are key factors influencing the size and percentage of clods, as asserted by Lyles and Woodruff, (1961).Bulk density demonstrates a linear increase over time across all treatments, potentially attributed to soil settlement and shrinkage at lower moisture contents, as suggested by Bajpai and Tripathi (2000).In the experiment conducted by Kukal and Aggarwal (2003), the bulk density of the 14 - 20 cm soil zone, observed after each rice season, exhibited a consistent increase over the period. The mean bulk density in the 14 - 20 cm soil layers notably rose from 1.53 Mg m^{-3} in 1994 to 1.66 Mg m^{-3} in 1995 and further to 1.70 Mg m^{-3} in 1996. Bulk density in the 14 - 20 cm zone increased annually, reaching 1.70 Mg m^{-3} in 1996. Shallow-puddled soils showed a smaller increase than normal-puddled ones, with a significant difference. Puddling at normal depth led to a compact layer persisting despite subsequent cultivation.According to Lal (1986), the surface layer of puddled treatments exhibited elevated bulk density at harvest compared to the no-till plots. It was found that puddling, which elevated bulk density, led to increased shear strength and a notable reduction in infiltration rate(Saroch and Thakur, 1991). As per observation, post-harvest, soil bulk density in the 0 -7.5 cm layer was 510% higher on compacted plots compared to puddled plots(Blake and Hartge 1986). In the 7.5 - 15 cm layer, bulk density on puddled plots equaled that of compacted plots due to particle settling and shrinkage.Bulk density variations were noted with uncontrolled factors, including soil type and depth. Numerous studies report an increase in soil bulk density during the transition from Conventional Tillage to No Tillage (Hill 1990; Gregorich *et al.* 1993).In a study, the bulk density of the soil initially rose with zero tillage compared to the traditional method of Tillage for the initial two years. However, over four years, it leveled off and eventually decreased under No-Tillage, likely due to enhanced soil structural stability (Voorhees and Lindstrom, 1984).Puddling-induced compaction was partially alleviated by organic manure. Organic manure, particularly green manuring, exhibited a greater buffering effect on changes in soil bulk density compared to farmyard manure (Aggarwal *et al.*, 1995).

Author	Bulk Density (Mg m^{-3})	Puddling Effect
Bodman and Rubin, 1948	0.83 - 1.16	Puddling reduces the bulk density of dense lowland soils
Sharma and Datta, 1986	0.53 - 1.16	Puddling leads to a reduction in bulk density
Kukal and Aggarwal, 2003	1.53 - 1.70	Consistent increase in bulk density observed over years
Mohanty, 2004	0.87 - 1.16	Soil bulk density increases from transplanting to harvest under puddling
Asenso *et al.*, 2022	1.4 - 1.8	Significant decrease in bulk density observed with moldboard ploughing and direct seeding
Dewanti and Mandang, 2022	0.71 - 0.98	Notable reduction in bulk density after puddling

Table .1: Bulk density and its effect

3.3. Penetration resistance

Soil penetration resistance is a critical parameter for assessing soil structure quality and overall health, serving as a vital indicator of the soil's ability to support agricultural productivity and plant growth. It is typically measured in megapascals (MPa) and reflects the resistance of soil to being penetrated by an object or root. The measurement of soil penetration resistance helps in understanding the compactness and consolidation of soil, factors that significantly affect root penetration, water infiltration, and, consequently, plant growth.

Soil penetration resistance, measured in MPa, is a key indicator of soil structure quality. Understanding and assessing this factor is crucial for evaluating overall soil health and productivity(Kalita *et al.*, 2020). According to Saroch and Thakur (1991), in puddled soil, penetration resistance notably increased from transplanting to harvest. In unpuddled soil, penetration resistance increased mainly in the surface 0-7 cm layer. Puddling is linked to increased bulk density and penetrometer resistance. Valera *et al.* (2012) found that mean dry bulk density at 30 cm depth remained unaffected by the number of passes or tractor type. Although successive passes significantly altered soil penetration resistance from the first pass onward, no statistically significant differences were noted after subsequent passes. Notably, alterations in penetration resistance were observed in the top 10 cm of soil.

Low penetration resistance hinders farm machinery use, as modern equipment with a ground pressure of 50 kPa may encounter difficulties due to high rolling resistance and slip. Compaction, sand addition, and drainage contribute to increased penetration resistance and shear strength. Soil penetration resistance rises consistently with depth (Sharma and De Datta1985).The variations in cone penetrometer resistance profiles at different depths, one day before transplanting, under puddling and compaction treatments. In compaction, penetrometer resistance peaked at 5 cm, while in puddling, a gradual increase was noted, reaching its maximum at 12 cm. Compaction primarily affected the 0–11 cm layer, with recultivation loosening the top 3–4 cm. Puddling, however, disrupted soil aggregates, capillary pores, and dispersed clay particles, reducing soil strength. Settlement of heavier particles occurred in the puddled layer, confirmed by the content of large particles (greater than 2 mm) in the 0–5 cm layer. Water flow and tractor wheel compaction likely contributed to increased PR in the 10–13 cm layer after puddling treatments (Hemmat and Taki, 2003).According to Rautaray (1997), the primary objectives of puddling are to minimize deep water percolation, decompose weeds, and ease the transplanting of rice seedlings by softening the soil. However, puddling results in soil compaction, raising both bulk density and soil penetration resistance.McCoy and Cardina (1997) assert that short-term no-till practices lead to increased penetration resistance and a reduced rate of oxygen diffusion in the soil. Yao(2015) conducted a three-year experiment on rice straw incorporation and tillage depth effects on soil properties. Shallow tillage increases penetration resistance more than deep tillage, affecting root growth. Rice straw incorporation reduced sinkage resistance, influenced soil structure regeneration, and correlated with soil organic C concentration.

There was a negative correlation between grain yield and soil bulk density, as well as soil penetration resistance. In tillage experiments, minimum tillage resulted in significantly higher grain yield, attributed to increased plant height, panicle length, and root length density, along with reduced soil penetration resistance (Sharma *et al.* 1988). Shallow and deep puddling also led to substantial yield increases, emphasizing the importance of mitigating soil penetration resistance for improved rice production. Increased penetration resistance to 1500 kPa may reduce crop root growth by 20% to 75% (Bengough, 1997). However, the limit of penetration resistance varies with the crop type (Bengough *et al.*, 2011). Penetration resistance measurements are lower with higher soil water content (Tarkiewicz and Nosalewicz, 2005). As a result, sinkage resistance and penetration resistance exhibit a negative correlation with soil organic carbon (SOC) concentration.

3.4. Hydraulic Conductivity

Wet tillage in rice, specifically puddling, diminishes hydraulic conductivity (Ks) by disrupting soil aggregates and reducing non-capillary pores. This process, as noted by Bodman and Rubin (1948), hinders the rapid transmission of water in the soil. It is observed that an increase in puddling intensity notably augmented the depth of the puddle and concurrently reduced the saturated hydraulic conductivity (Ks) of the puddled layer(Singh *et al.* 2004). Puddling-induced reduction in hydraulic conductivity is likely attributed to the destruction of soil aggregates and the decrease in non-capillary pores, (Sharma and Dutta,1985, Mambani*et al.*,1989). Puddling diminishes hydraulic conductivity by elevating topsoil clay content (Lal, 1986).An increase in puddling intensity significantly augmented the depth of the puddle and concurrently reduced the saturated hydraulic conductivity of the puddled layer(Singh *et al.* 2004). The reduction in the value of hydraulic conductivity may be attributed to the elimination of transmission pores resulting from intense puddling with a power tiller and a puddler, (Barua *et al.* 2007). Puddled soil, characterized by closely packed parallel particles, diminishes hydraulic conductivity (Ks) and percolation rate, as highlighted (Datta,1981). Puddling led to a significant reduction in hydraulic conductivity, decreasing it from 20.5 to 1.6 mm-1 in sandy clay loam (Pande, 1975).

Puddling not only diminishes percolation losses by reduction in soil hydraulic conductivity but also aids in control of weed and creates a medium soft for effective transplanting of rice seedlings, as discussed by Datta (1981), Sharma and Datta (1986), and Kirchhoff *et al.* (2000). The hydraulic conductivity of compacted soil cores exhibited a significant decrease as bulk density rose from 1.5 - 2.0 Mgm^{-3}, as observed by Patel and Singh (1981). Saloke*et al.* (1993) observed a decrease in hydraulic conductivity with an increasing number of passes of a rotavator at all speeds. The decrease in hydraulic conductivity is attributed to the sealing of pore spaces by finer particles in the hardpan at the top of the.Behera (2009) experimented, finding the minimum hydraulic conductivity at 30 Days After Planting (DAP) in Peg-type puddler with two passes (0.257 mm hr^{-1}), significantly lower than Peg-type puddler with one pass (0.315 mm hr^{-1}) but comparable to rotary puddler of one pass (0.270 mm hr^{-1}). No substantial variation was observed at 60 DAP. Hydraulic conductivity reduction in puddled soil, attributed to the clogging of pore channels by settled particles, was evident in all treatments. The correlation revealed that as bulk density increased, hydraulic conductivity decreased, with a lower rate of decrease at higher bulk density.

The field monitoring of the bulk density of the soil and penetrometer resistance. Saturated hydraulic conductivity was assessed using a constant head permeameter on 100cm^{3} cores. Inconsistent trends were observed in saturated hydraulic conductivity concerning tillage or nitrogen treatment. Although variable, hydraulic conductivity generally remained high, with variations expected due to measurements on small cores where cracks near cylinder walls could influence water flux. Puddled treatment surfaces exhibited higher bulk density and lower hydraulic conductivity at harvest compared to no-till plots(Lal, 1986).An experiment by Kukal and Aggarwal (2002), observed a decrease in hydraulic conductivity of the puddled layer with increased puddling intensity, ranging from 0.064 cm h^{-1} with medium-puddling to 0.009 cm h^{-1} with high-puddling. Simultaneously, the hydraulic gradient between puddled and unpuddled layers increased with puddling intensity. The hydraulic conductivity of the puddled layer, corresponding to a puddle water depth (PWD) of 7 cm, was calculated using Darcy's Law. In high-puddled plots, the reduced hydraulic conductivity of the puddled layer led to water accumulation, contributing to under-bund percolation. Puddling resulted in a 76% reduction in hydraulic conductivity with medium-puddling and an 86% decrease with high-puddling compared to the same layer in puddled plots.The primary objective of puddling rice soils is to reduce hydraulic conductivity (Sanchez, 1973). Hobbs *et al.* (2002) determined that puddling significantly decreased hydraulic conductivity throughout the rice season. In direct-seeded plots, it was 5.68 and 3.25 times higher at the surface and subsurface layers compared to transplanting. At 20 Days After Transplanting/Days After Sowing (DAT/DAS) and at harvest, Singh *et al.* (2002) found that hydraulic conductivity was 2.4 and 1.2 times higher in the surface layer compared to the subsurface layer. Puddling induces alterations in soil physical conditions, diminishing hydraulic conductivity and infiltration rate for facilitated submergence. This practice aids in preventing nutrient loss through leaching, and weed control, and enhances nutrient availability through the creation of a reduced soil layer and other chemical property changes (Ponnamperuma, 1976). Kalita *et al.* (2020) studied that the distribution of water-stable aggregates (WSA) increased with decreasing size, and surface soil's saturated hydraulic conductivity during rice harvest significantly decreased with conventional tillage. Puddling using a helical blade puddler or power tiller, however, further reduced hydraulic conductivity compared to traditional practices.

4. PUDDLING PARAMETERS

4.1. Puddling Index

The puddling index is a crucial parameter used to assess the effectiveness of soil puddling in rice cultivation. After the final puddling operation, a 250 ml soil sample is collected in a graduated glass cylinder and allowed to settle for 48 hours. The volume of the settled soil sample (Vs) is then measured, along with the initial volume (V) before settlement. The puddling index is calculated using the formula:

$$Puddling\ Index = \frac{\mathrm{Vs}}{\mathrm{V}} \times 100$$

One notable limitation of this index is its dependency on the depth of water standing in the field. Despite this drawback, studies have shown a significant increase in the puddling index of rice soils when mechanical puddling implements are employed, surpassing traditional farming practices. The puddling index, uniformity index, and softness index measurements as indicators to assess the quality of puddling in their study(Dewanti and Mandang 2022).Behera *et al.* (2007) observed a noteworthy rise in the puddling index with increased puddling levels. Dhiman *et al.* (2001) observed a greater decrease in bulk density of surface soil (0-15cm) compared to sub-surface soil conditions (15-30cm), attributing it to a combination of high puddling index and puddling depth. However, significant bulk density augmentation occurred solely with the rotary puddler, likely attributed to its higher puddling index. In an experiment (Prasanthkumar*et al.*, 2020), increasing the number of passes from single to double did not significantly affect puddling quality. The power tiller-operated rotary tool achieved the highest puddling index (61.18%).The rotavator, with a slightly lower puddling index (58.29%) due to its larger width, was deemed the best overall among the puddling techniques studied. Verma and Dewangan (2006) reported that the highest puddling index value was observed when using a tractor-attached cage wheel and rotavator in their experiment.Mechanical puddling implements led to a significant increase in the puddling index (%) of rice soils compared to traditional farmers' practices, as noted in the study by Kalita *et al.*, 2020.

A study on the puddling index revealed significant increases with higher puddling levels across various equipment. Rotary puddler exhibited the highest index, notably at three passes.Apeg-type puddler, showed an increased puddling index in the second year, possibly due to well-prepared initial field conditions. The study suggests that close peg spacing contributes to a higher puddling index in peg-type puddlers compared to cultivators. Moreover, while there was a considerable increase in the puddling index with higher puddling levels, bulk density increased significantly only with the rotary puddler, possibly due to its higher puddling index, causing the destruction of macro pores(Behera *et al.* (2007).In the series of experiments, it was found that Treatment P2-Peg type puddler with two passes demonstrated a significantly higher puddling index

(30.13%) compared to P1- peg type puddler with one pass (19.40%) and R1- rotary puddler with one pass (24.60%). Puddling involves compression and shear deformations, with rotary puddler's shear stress disintegrating soil particles effectively. The angular blade orientation in rotary puddlers enhances churning, aligning with the observed increase in the puddling index(Behera, 2009). This supports findings by Salokhe*et al.* (1993) and Behera *et al.* (2007), confirming that the increased level of puddling intensifies soil manipulation, resulting in a higher puddling index.It was found that the rotavator and pulverizing roller attachment were effective in developing a puddle bed based on the puddling index and percolation rate(Saimbhi, 2016). The pulverizing roller attachment exhibited the deepest puddle bed with the lowest development cost, although the cultivator-planker showed a slightly higher yield compared to the rotavator. The pre-puddling tillage intensity did not affect the puddling index, but increasing puddling intensity significantly raised it. The index was unaffected by clay content in surface soil layers, suggesting it is a distinct indicator of clay content, especially in sandy loam soils(Kukal and Aggarwal 2004).

4.2. Percolation rate

Percolation rate, a critical aspect of soil hydrology, refers to the rate at which water moves downward through the soil profile, influencing water availability for plant uptake and groundwater recharge. Understanding percolation rates is particularly crucial in agricultural contexts, such as rice production, where water management plays a significant role in crop productivity and resource conservation.

In rice production, coarse-textured soils experience significant water and nutrient losses through deep percolation. Enhancing productivity involves minimizing water percolation and nitrogen leaching, as suggested by Kar *et al.* (1986).About 75% of water applied to rice crops is lost through deep percolation during field submergence. Cultivating rice under puddled conditions is employed to minimize percolation losses, aiming to enhance water and nutrient use efficiency in plant cultivation (Swaminathan, 1972).According to Patel (2019) and Aimrun*et al.* (2010), puddling reduces percolation, leading to prolonged standing water in the field. This, in turn, decreases the irrigation requirement. The reduction in water loss through percolation is attributed to the structureless soil and the formation of a tillage pan. This observation aligns with findings by Choudhury *et al.* (2007) and Wang *et al.* (2004).

Soil compaction emerges as a cost-effective alternative to puddling, reducing percolation losses and rice water requirements. Achieved through heavy roller passes near the lower soil plastic limit, compaction allows mechanization in wetland rice cultivation, overcoming the challenges of puddling, particularly on medium and coarse-textured soils (Ghildyal, 1978).Arora(2006) emphasized that alterations in soil bulk density and saturated hydraulic conductivity, driven by variations in puddling intensity, play a pivotal role in influencing percolation rate and water usage during the puddling process.The reduced water requirement in the compaction treatment is attributed to lower permeability, leading to decreased percolation. Compaction interlocks aggregate, minimizing macropore volume and subsequently reducing percolation losses (Achar and Sood, 1992).In an experiment by Anjum, 2019, Water loss through seepage plus percolation was notably higher in unpuddled soils compared to puddled soils, and it increased with the intensity of puddling, ranging from 976 mm to 1098.6 mm. The infiltration rate of soil significantly decreased with increasing puddling intensity in furrows. The maximum number of puddling passes in furrows resulted in the highest yield, reaching 653.2 gm^{-2} compared to 450.5 gm^{-2}under the control treatment. Maximum water productivity (0.5724 kgm^{-3}) was achieved with six passes of puddling, while the minimum water productivity (0.26 kgm^{-3}) was observed in the control treatment. The transitioning from low to medium puddling intensity reduced mean seasonal percolation losses by 78.3 cm in sandy loam and 50.8 cm in silty clay loam soils. Furthermore, increasing puddling intensity from medium to high led to a decrease in mean seasonal percolation losses by 37.9 cm in sandy loam and 39.3 cm in silty clay loam soil(Singh *et al.* 2001).The depth of flooding had contrasting effects on percolation in different soil types. For somewhat porous, non-swelling soils, the percolation increased with greater flooding depth, while low-percolating soils experienced reduced permeability. Tabbal *et al.* (1992) found a decrease in percolation rate from 20 mm per day under 2 - 5 cm puddling water depth (PWD) to 9 mm per day in the continuously saturated regime (PWD = 0 cm) in clay loam soil. In contrast, a study reported only a slight increase in percolation loss with increasing water depth(Ferguson, 1970).

In a study, there was a decrease in percolation rate (PR) in sandy loam soil from 14 mm/day with low-puddling (one pass of plowing followed by planking) to 10 mm/day with high-puddling (four passes of plowing followed by one planking). The extent of percolation loss reduction is linked to puddling intensity, with high intensity contributing to hardpan development and adverse effects on subsequent wheat crops' growth and yield(Aggarwal *et al.*, 1995). The nonlinear reduction in water flux through soils with increasing puddling depth in a column study(Sharma and Bhagat, 1993)that puddling significantly decreased the water percolation rate by up to 92%, depending on puddling depth, intensity, and soil texture. Soils with higher organic matter exhibited a more pronounced reduction in percolation rate. A puddling depth of 10 cm at high intensity proved most effective in limiting the settling of suspended particles and water percolation(Sandhu and Singh, 2001).

The study employed a method to assess the creation of an impervious layer using infiltration as an indicator. A 15 cm diameter pipe filled with water was used, and the water level was recorded at 3-hour intervals to analyze the relationship between infiltration rate and duration. Analysis of variance for sandy loam soil puddling index revealed significance at the 1% level, with the power tiller-operated rotary tool exhibiting the highest puddling index. (Prasanthkumar*et al.* 2020; Prasanthkumar*et al.* 2019; Chhina, 2015). The number of passes did not significantly affect the puddling index. Increasing passes led to a higher puddling index and reduced infiltration rate, with the power tiller, operated rotary tiller showing the highest puddling index and lowest infiltration rate. Rotavator puddling was second, covering more area than the power tiller. In conclusion, rotavator puddling is deemed suitable for sandy loam soil among the tested techniques.

The decline in percolation rate (PR) over time in both medium and high-puddling experiments. Increased depth of ponding water correlated with a higher percolation rate. Infiltration rings recorded percolation rate values of 1.8%, 38.8%, and 42.1% lower than those in whole plots, indicating under-bund losses. The seepage ratio increased with intensified puddling, highlighting the direct relationship between under-bund percolation and puddling intensity. Medium-puddling significantly reduced mean PR by 55%, 54%, and 58% in 1994, 1995, and 1996, respectively, compared to unpuddled plots. High puddling did not further decrease the percolation rate significantly, despite a higher sediment density. In unpuddled soils, PR remained relatively constant, while in puddled soils, it decreased over time, demonstrating the impact of settling finer soil particles on surface permeability(Kukal and Aggarwal, 2002).

In an observation a 14-16% decrease in percolation losses with increased puddling intensity, leading to a 10-25% reduction in irrigation water requirement. Puddling depth did not impact percolation losses or irrigation water applied (Kukal and Aggarwal, 2003). Mohanty (2004) found that puddling, on average, reduced seepage plus percolation, with the extent of reduction influenced by puddling intensity. Coarse-textured and organically rich soils responded more to puddling in reducing percolation losses. Sharma and Datta, 1986 reported that there remains a necessity to formulate a comprehensive puddling index aligning with the dual goals of achieving soil softness for easy transplanting and minimizing percolation rates for water and nutrient conservation. An integrated assessment incorporating bulk density and percolation rate is recommended. Exploring the alteration in the ratio of silt plus clay dispersed in water to the actual silt plus clay in the soil, pre- and post-puddling, may also serve as a viable index for evaluating puddling effectiveness. The puddling serves multiple purposes, such as weed suppression, minimizing water percolation through the formation of a hardpan, and facilitating energy-intensive rice transplanting by preparing beds(Lal 1986).

5. Conclusion

In Conclusion, puddling's impact on soil structure is complex, influenced by factors like soil texture and rice cultivation methods. While it can improve sub-soil for rice, it compromises structure for upland crops, leading to shrinkage and weakened structures. Bulk density may increase, affecting water transmission and root growth. Organic manure can help mitigate compaction. Soil penetration resistance affects soil health and productivity, highlighting the need for effective management practices. Wet tillage practices like puddling reduce hydraulic conductivity, impacting water movement and nutrient availability. Puddling quality assessments are crucial for sustainable rice farming. Percolation rates in rice cultivation are influenced by puddling intensity and soil properties, informing water management strategies.

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