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Puddling and its effect on soil physical properties and growth of rice and post rice crops: A review

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Abstract
Puddling is an important operation of wetland rice cultivation which facilitates transplanting, weed control and reduces percolation loss of water and nutrients. However, besides these advantages, the puddling creates soil physical condition detrimental to post rice crops. The puddling index (%) of rice soils increased significantly over farmers practice when puddling was done by mechanical puddling implements. The bulk densities (Mg/m^3) of surface layers were comparatively higher than the sub-surface layer irrespective of different tillage treatments for puddled rice cultivation. The percent distribution of water stable aggregates (WSA) in various size fraction increased with decreasing size range and the Saturated hydraulic conductivity (K_s) of surface soil measured at harvest of rice crop was significantly reduced by tillage. Increased intensity of puddling increased significantly the depth of puddled layers and crack dimensions however puddling reduced both seepage plus percolation loss of water. The dry matter yield (g/m^2) and grain yield (kg/ha) of rice increased with increase in puddling intensity. Rice yields were highest under the traditional puddling techniques using draught animal traction but puddling with a rototiller reduced yield because of insufficient depth of puddling. The dry cultivation may have reduced yield due to increased soil strength of the puddled layer and both are thought to limit root development. The grain yield of rice over the years under no-till mechanical transplanted rice (MTR) was higher than conventional puddled transplant rice (CPTR). The yields of post rice crops are usually very low and well below the potential yield which is commonly associated with the adverse effect of soil physical conditions induced by puddling during land preparation for the rice crop. Root growth into the subsoil is generally limited, resulting in low plant available water for post-rice crops.

Keywords: Puddling, post rice crops, soil physical properties, rice

Introduction
Rice is grown on 6 continents and in more than 100 countries. It is produced in different environments and in many ways. Worldwide about 148 million ha are planted to rice (*Oryza sativa* L.) each year, taking into account double and triple cropping. About 90 percent of this area is in Asia and two thirds in South and South-East Asia, where rice is the most dominant crop grown during the wet season. When wetland rice is included in a cropping system, the soils undergo unique changes in physical properties (Bhagat, 2003) [5]. Wet tillage or puddling has become synonymous with wetland rice culture and it refers to the destruction of aggregated condition of the soil by mechanical manipulation within a narrow range of moisture contents above and below field capacity (0.03 MPa), so that soil aggregates lose their identity and the soil is converted into a structurally more or less homogenous mass of ultimate particles.

Throughout South East Asia puddling is used to prepare soil for lowland rice. It involves cultivation of the soil after it has been softened by flooding for several days and creates a layer of soft mud which often overlies adense plough pan. Puddling and the maintenance of flooded conditions create favourable conditions for rice by aiding weed control, making seedling transplanting easier, creating reduced conditions which improve soil fertility and reducing deep percolation of the standing water in which rice is grown but in terms of the degree of alteration of soil structure, puddling is a rather extreme form of tillage, because it results in aggregate breakdown and the destruction of macropores.

Puddling or wet tillage coupled with submerged conditions are responsible for making drastic effects on soil physical characteristics of rice soils. These effects can be continued either for short or long time. During rice-rice or rice-wheat cropping sequence the system undergoes transition from saturated to unsaturated conditions. While this happens, the soil physical properties again undergo changes.

In several rice producing countries, production of upland crops is an important means to food security and to exploit the residual soil water following paddy harvest. Since the soil physical requirements for establishment and growth of upland crops are different from those for paddy, so soil physical properties that may limit the emergence of post rice crops in rice soils, and soil management techniques that will alleviate the soil physical constraints to establishment of those crops. The causes of low yields of post rice crops are often poor crop establishment and inferior root growth due to adverse physical conditions of the soil which, in turn, are caused by the wet cultivation (puddling) undertaken for paddy rice. Yields are also limited by nutritional and biological constraints. In the dry season following a lowland rice crop, yields of post-rice crops are generally low, despite adequate water commonly being available in the soil profile to grow a potentially high yielding dry season (DS) crop without irrigation.

The tillage related problems in the cropping system like rice–wheat does not end with rice. As soon as rice is harvested in the first or second week of November, wheat has to be seeded as soon as possible; the optimum for wheat seeding is mid-November. However, wheat seeding generally is delayed due to moist field conditions, which makes cultivation impossible. Many farmers therefore broadcast wheat in moist fields left after rice harvest. This also permits them to take advantage of residual moisture in rice fields and permits timely sowing of wheat. Traditional cultivation of land and sowing wheat generally delays wheat sowings to late November or early December resulting in reduced yield. However, yields are also low in direct seeded wheat due to serious weed problem (Singh *et al*., 2001) [56]. Although, puddling helps in weed management and reducing water loss through percolation nonetheless it deteriorates the soil environment for post-rice crops (Sharma and De Datta, 1985) [50]. This results in erratic stand establishment of post-rice crops owing to poor contact of seed with soil. Subsurface compaction of soil caused by puddling may induce the drought to post-rice crops by restricting the root development (Kirchhof *et al*., 2000) [25]. Most farmers in rainfed lowland areas do not grow secondary crops after rice. When they do, the yields of these crops are usually very low and well below the potential yield of these crops. These low yields are commonly associated with the adverse effect of soil physical conditions induced by puddling during land preparation for the rice crop. Root growth into the subsoil is generally limited; resulting in low plant available water for post-rice crops.

Mechanics of puddling

The term puddling was defined as “the destruction of the aggregated condition of the soil by mechanical manipulation within a narrow range of moisture contents above and below field capacity (0.3 bars), so that soil aggregates lose their identity and the soil is converted into a structurally more or less homogeneous mass of ultimate particles.” After puddling, a soil is called a puddled soil, defined as a “dense soil with a degraded soil structure; dominated by massive or single-grain structure, resulting from handling the soil when it is in a wet, plastic condition so that when it dries it becomes hard and cloddy” (Gregorich *et al*., 2001) [22]. Ghildyal (1978) [20] defines a puddled soil as follows: “A puddled soil is one whose structure has been destroyed, whose aggregates have lost their identity, and which has been converted into a structurally homogeneous mass of fine aggregates and textural separate.” The degree of puddling depends on the soil and cultural practices. A clay content exceeding 20% favours puddling (De Datta, 1981) [12]. Smectitic clays puddle more readily than Kaolinitic or oxidic. Sodium clays puddle easier than calcium clays. As the content of organic matter or that of iron and aluminium oxides increases soils are less readily puddled (Sanchez, 1976) [46].

The changes brought about by puddling are not static. The soil particles settle and undergo stratification into clayey, silty and sandy layers, the bulk density increases, the moisture content decreases in spite of the soil being flooded and gases are trapped in the puddled layer. The thickness of the oxidized surface layer increases during the season and reddish-brown streaks and mottles are visible in the reduced puddled soil. When the soil is drained and dried, it cracks. Alternate drying and wetting and tillage regenerate aggregates. Soils high in organic matter or iron and aluminium oxides are easier to regenerate than others (Sanchez, 1976) [46].

Puddling leads to

- Increasing its water holding capacity due to increase in micro porosity of soil.
- Makes manual transplanting easier by reducing shear strength of soil.
- Reduction in air filled pore volume by replacing water.
- Increase in moisture suction.
- Better weed control due to lack of oxygen and shift in weed flora.
- Improves soil fertility and productivity of the soil.
- The highest yield is generally reported from wetland cultivation.

Therefore, a great prominence has been on development of suitable set of practices and machinery for wetland rice cultivation. Paddy crop requires a large amount of water and hence, to reduce irrigation requirement, puddling is to be done in rice soils before sowing / transplanting.

The benefits of puddling for rice listed by De Datta (1981) [12] include

- Reduced draft requirements for tillage
- Easy transplanting
- Increase in nutrient availability
- Reduces soil permeability
- Preserves aquatic, anaerobic conditions
- Controls weeds, improves water conservation

The main disadvantages of puddling are (De Datta, 1981) [12]

- Excessive water use,
- Low traffic ability,
- Difficulty of regenerating soil structure for the dryland crop following wetland rice.
- High water requirement (i.e. about 250 mm of water is needed), hindrance toregeneration of soil structure and impervious layer which impeded root development.
- Puddling makes the soil chemically different from other soils.
- A puddled soil system is characterized by presence of reduced soil layer and hard pans or plough pan (compacted layer) resists root penetration of following crop.
- The degree of soil compaction, however, varies with soil type, cultivation practices, wetting and drying cycles, temperature and years of crop production.
- Destroys soil aggregates, breaks capillary pores, disperses fine clay particles and lowers soil strength in the puddled layer.
- Can cause water logging

- Forms large clods in finer textured soils preventing seed-soil contact
- Most important and energy consuming operation under wetland cultivation.

Effect on soil physical properties

Bulk density is a soil physical parameter used extensively to quantify soil compactness. The bulk density varies with management as well as with inherent soil qualities. Because of dependence on inherent soil properties, measurements of bulk density are of limited value as a measure of the effect of management of soil compactness when soils with different inherent characteristics are compared. Penetration resistance (MPa) of the soil can be regarded as a factor determining the quality of its structure. Bulk density is the most fundamental soil physical property and is related to natural soil characteristics such as texture, organic matter, soil structure (Chen *et al.*, 1998) [10], gravel content (Frazen *et al.*, 1994) [15] and varies over the year due to the action of several processes: freezing and thawing (Unger *et al.*, 1991) [65], kinetic energy of rainfall (Cassel, 1982) [9] and loosening by root action and animal activity. Puddling decreases the bulk density of surface layer of clay soil initially due to destruction of aggregates and corresponding loss of inter aggregates or transmission pores and increase in inter micro aggregates and inter domain pores. A declination in the bulk density of surface layer of low land clay from 0.83 to 0.53 Mg/m^3 and that of clay loam from 1.16 to 0.81 Mg/m^3 due to the action of puddling was found by Sharma and De Datta (1985) [50]. Similarly high reduction in bulk density of surface soil (0-15cm) than sub surface (15-30cm) soil was observed by Dhiman *et al.* (2001) [13] due to high puddling index and depth of puddling. But with the increment of time, as particles settled down, bulk density of lowland submerged soil increased. Sharma *et al.* (1995) [53] reported that transplanted rice caused significantly increased bulk density of soil over its initial status than direct seeded rice after two years of experimentation. Bajpai and Tripathi (2000)[2] remarked that puddling for rice planting significantly reduced (1.30 Mg/m^3) bulk density of surface layer (0-0.06 m) only at tillering stage. While at harvest, the bulk density of puddled plots increased and was found to be significantly higher (1.49 and 1.70 Mg/m^3) than that of unpuddled plot (1.44 and 1.64 Mg/m^3) at both depths (*i.e.* 0-0.06 and 0.12-0.18 m) respectively. Hobbs *et al.* (2002) [23] found that the puddling increased bulk density in surface (1.53 Mg/m^3) in the early crop season compared to the unpuddled plots for direct seeding (1.41 Mg/m^3) in silty loam soil. At the harvest, the soil was more compact in both surface and subsurface layer. Singh *et al.* (2002) [59] found that bulk density was significantly lower in puddled plots (1.31 Mg/m^3) compared with direct seeding without puddling (1.42 Mg/m^3) in surface soil (0-7 cm) at 20 days after transplanting. Later at harvest, these differences narrowed. In subsurface soil (12-19 cm), differences in bulk density in direct seeding without puddling and transplanted plots were not significant. Sharma *et al.* (1988) [49] reported that bulk density at 30 days after transplanting (DAT) and at harvesting was highest (1.49 and 1.52 Mg/m^3) in the rotary puddler plots and lowest (1.44 and 1.46 Mg/m^3) in the direct seeding without puddling plots at 0-5 cm and 15-20 cm depth respectively. Three puddling intensities i.e. no-puddling and puddling by four and eight passes of 5 hp power tiller were evaluated by Mohanty *et al.* (2004) [35] and observed that the soil bulk density and penetration resistance (PR) increased significantly from transplanting to harvest in puddled soil, but in unpuddled soil penetration resistance significantly increased only at the surface 0-7 cm layer. Puddling is reported to increase the soil bulk density and penetrometer resistance (Saroch and Thakur, 1991) [48]. Rawat *et al.* (1996) [42] reported increase in bulk density and decrease in water stable aggregate as a result of puddling. Ghildyal (1982) [21] also reported an increase in soil density below the puddled layer due to physical compaction during the puddling process. Kirchhof *et al.* (2000) [25] reported that increase in puddling intensity from medium to intensive significantly increased the bulk density. In normal-puddled plots, the average bulk density of 14-20 cm soil layers was significantly higher (1.74 g/cm^3) than that of shallow puddled plots (1.57g/ cm^3) at the end of 3 years of study. Similar trends were observed in case of soil penetration resistance (Kukal and Aggarwal, 2003) [28].

The above cited literature indicates that soil bulk density decreases at the time of intensive puddling but with the settling of soil particles it goes on increasing till the maturity of the crop and hence soil bulk density after the harvest of the rice crop is more in conventional tillage than reduced tillage. Rahman (1991) [40] observed that a combined effect of tillage and puddling during long-term wheat and rice cultivation produces a dense layer below the surface of the soil. Formation of this dense layer enables the topsoil to store more water. Utomo *et al.* (1996) [66] in Indonesia also found that the puddling is necessary in course texture soils to reduce percolation rate and ensure that submerged conditions can be maintained whereas on the other hand, in finer textured soils, puddling is not necessary, and minimum disturbance/cultivation may result in a significant saving of energy to the farmer. The wet tillage in rice *i.e.*, puddling decreases hydraulic conductivity due to destruction of soil aggregates and reduction of non capillary pores responsible for rapid transmission of water in soil (Bodman and Rubin, 1948) [7]. The closely packed parallel particles in puddled soil reduced hydraulic conductivity (K_s) and percolation rate (De Datta, 1981) [12]. Similarly, a reduction in hydraulic conductivity was reported by Saloke *et al.* (1993) [45] with the increase in number of passes of rotavator at all speeds. The reduction in K_s was because of sealing of pore spaces by finer particles in the top of the hard pan. Puddling decreased the hydraulic conductivity of lateritic sandy loam from 1.9 to 0.2 mm/hr (Varade and Ghildyal, 1967) [68] and sandy clay loam from 20.5 to 1.6 mm/hr (Pande, 1975) [37]. The hydraulic conductivity of compacted soil cores drastically decreased as the bulk density increased from 1.5 to 2.0 Mg/m^3 (Patel and Singh, 1981) [39]. It was 75.0, 20.2, 5.2, 0.1, 0.02 and 0.00 mm/hr at bulk density of 1.5, 1.6, 1.7, 1.8, 1.9 and 2.0 Mg/m^3, respectively. Bajpai and Tripathi (2000) [2] observed that the K_s of the 0-0.06 m soil depth reduced to one sixth and one half due to puddling at tillering and at harvesting stages, respectively. Contrarily, Tiwari and Tomar (2002) [63] compared three rice cultivation methods *i.e.*, direct seeded (M0), lehi (M1) and transplanted rice (M2) and revealed that K_s increased significantly in M2 (10.25×10^{-7}m /sec) and in M1 (9.43×10^{-7} m/sec) over M0 (8.33×10^{-7} m/sec) and significantly decreased to 5.56 and 4.79×10^{-7} m/sec at harvest but in M0 it remained at par. The hydraulic conductivity was 2.4 and 1.2 times higher in surface than sub surface layer at 20 DAT/DAS and harvest respectively (Singh *et al.*, 2002) [59]. Hobbs *et al.*, (2002) [23] evaluated that puddling considerably reduced hydraulic conductivity throughout the rice season. It was 5.68 and 3.25 times higher at surface and sub surface layer in direct seeded plots than transplanting. This difference narrowed at harvest. Puddling reduces hydraulic conductivity not only through increasing the topsoil clay content (Lal, 1986) [32], but also through the mechanism of clay dispersion, particularly in clayey soils (So & Cook, 1993) [61]. The decrease in hydraulic conductivity by puddling was probably due to destruction of soil aggregates and reduction of non-capillary pores (Sharma and De Dutta, 1985; Mambani *et al*., 1989) [50, 34]. Increase in puddling intensity significantly increased depth of puddle and decreased saturated hydraulic conductivity (K_s) of the puddled layer (Singh *et al*., 2001) [56]. Saturated hydraulic conductivity (K_s) of surface soil measured at harvest of rice crop was significantly reduced over farmers practice (puddling by 3 passes of cross ploughing) when puddling was done by a helical blade puddler and power tiller operated case wheel and rotavator. Reduction of K_s value may be due to elimination of transmission pores due to intense puddling by puddler and power tiller (Barua *et al*., 2007) [3]. Sandhu and Singh (2001) [47] also showed that puddling decreased the percolation rate of water by up to 92% depending on the depth and intensity of puddling and soil texture. Soils with higher organic matter content responded more to puddling in terms of reduction in percolation rate. A puddling depth of 10 cm at high intensity of puddling was more effective in reducing the rate of settling of suspended particles and percolation rate of water. The process of water percolation was studied by Kukal and Aggarwal (2002) [28] in a puddled sandy loam rice field with three puddling intensities. Percolation losses of water decreased with medium-puddling by 54-58%, but it remained unaffected by increased puddling intensity as well as puddling depth. Percolation rate (PR) decreased with time with both medium and high puddling intensity but it increased with increased depth of ponding water. Kukal and Aggarwal (2003) [29] recorded the 14-16% decrease in percolation losses with the increase in puddling intensity whereas the requirement of irrigation water decreased by 10-25% with increased intensity of puddling. Puddling depth did not affect percolation losses or the amount of irrigation water applied. Mohanty *et al.* (2004) [35] evaluated three tillage treatments *viz*., no puddling (P0), puddling with four (P1) and eight (P2) passes of power tiller under the same nutrient management practice and concluded that puddling, on an average, reduced seepage plus percolation to 5.6, 2.8 and 2.4 mm/h in P0, P1 and P2, respectively. Thus puddling reduces percolation losses of water in rice fields, the extent of reduction being a function of intensity and depth of puddling. Course textured soils and soils with high organic matter respond more to puddling in terms of reducing percolation losses of water. Yadav *et al*. (2011) [70] showed that there was greater cracking on puddled soils than on non-puddled soils during soil drying, and that this was associated with a faster rate of drying in the puddled soil. Mohanty *et al*. (2006) [36] also found that the surface area of cracks was larger in puddled soils than in non-puddled soils.

Effect on rice

Puddling is used to prepare soil for irrigated rice throughout south-east Asia creating a soft mud often over a plough pan. Reddy and Hukkeri (1983) [43] studied four tillage methods *viz*., puddling once, puddling twice, compaction of the soil surface and preparation of the seedbed by conventional ploughing and reported that the field puddled twice produced maximum dry matter accumulation, plant height, number of tillers at harvest, panicle length, number of filled grains/panicle, and 1000-grain weight, maximum grain and straw yields of 4.5 and 7.0 t/ha, respectively. Transplanting rice seedlings into unpuddled field depressed establishment of plants/seedlings, early growth, tiller initiation and number of tillers/plant, but at high soil temperature (25ºC) growth was better than in puddled fields (Kumano, 1985) [30]. Singh *et al.* (2001) [55] reported that with the increase in puddling intensity from no puddling (P0), two discing + one planking (P2), and four discing + one planking (P4), significantly increased leaf area index and dry matter production whereas Furuhata *et al.* (2005) [17] in Japan found that the seedling establishment rates of rice two weeks after sowing were lower in over-puddled plots compared to the normally puddled plots, especially when wheat straw was applied. Sharma and De Datta (1985) [49] revealed that bulk density and soil strength were the main factors affecting grain yield of rice crop. Sharma *et al.* (1988) [48] at IRRI, Philippines found the negative correlation of grain yield with bulk density and soil penetration resistance. Yield components and paddy yields of rice grown in a puddled black cotton soil were significantly increased compared with a non-puddled soil. The yields obtained in soils puddled to a depth of 10 cm were higher than in soils puddled to depths of 20 or 30 cm (Bhalerao and Nimkar, 1985) [6]. Whereas in plots where puddling was not practiced, grain number/panicle and percentage of productive tillers increased and panicles/hill decreased, grain: straw ratio was higher but percentage of ripened grains was low. Average brown rice yield was 645 g/m^2 and decreased by 1-10% and 2-3% compared with puddled fields in soils with low and high permeability, respectively (Kumano *et al*., 1985) [30]. Ali *et al.* (1992) [1] compared four tillage treatments and reported that complete puddling gave the highest 1000-grain weight, total and head rice recoveries as compared to partial puddling. Singh *et al.* (1984) [53] reported that the rice transplanted on a puddled soil gave significantly higher paddy yields than when transplanted on an unpuddled soil. Das and Choudhary (1985) [11] found that puddling thrice at 7 days interval, puddling twice or puddling twice after preliminary tillage (local practice) gave yields of 3.66, 3.43, and 3.05 t/ha, respectively. Singh *et al.* (1995) [54] at Ludhiana compared 3 levels of puddling for rice cultivation *viz*., no puddling, 2 runs of a tractor-drawn cultivator in standing water, each followed by planking, and 4 cultivations and 4 plankings and found that the yield averaged 2.22, 2.54 and 3.26 t/ha with 0, 2 and 4 puddlings, respectively. Conversely Utomo *et al*. (1993) [66] reported that rice yield was not significantly affected by degree of puddling. Growth and yield of subsequent crop was increased by decreasing puddling intensity. Kirchhof and So (1995) [26] also showed that soil puddling intensity had no effect on rice yields except on coarse textured soils. In another study, Kirchhof and So (1996) [27] reported that puddling could be reduced without affecting rice yields, except on sandy soils. Further they reported that compaction decreased percolation rates, except on clay soils, and tended to reduce rice yields. Compaction was likely to be beneficial for rice on coarse-textured soils. Parihar (2004) [38] reported that conventional (3 passes with cultivator + 2 plankings) and reduced (through rice puddler) puddling had not much significant difference in paddy yields. Bajpai and Tripathi (2000) [2] reported that both puddling and non-puddling was equally effective for getting higher grain yield of rice. However, non-puddling of rice produced a significantly higher wheat grain yield than that of wheat followed by puddled rice. Kukal and Aggarwal (2003) [29] found that puddling, even though reduces percolation losses of irrigation water in rice production, it also results in yield decline of wheat (*Triticum aestivum* L.) that follows the rice crop in the cropping sequence because of subsurface compaction. Singh *et al.* (2004) [56] reported that rice transplanted after puddling by four passes of rotary puddler increased rice yield by 9.3 per cent compared to direct sowing without puddling but wheat yield was recorded highest under direct sowing without puddling treatment. Tripathi *et al.* (2005) [63] studied four tillage treatments for rice *viz*., puddling by four passes of rotary puddler (PR), reduced puddling (ReP), conventional puddling (CP) and direct seeding without puddling (DSWP) to optimize tillage in rice-wheat system. They found that rice yield in the rotary puddler (PR) plots was highest and statistically equal to that in the reduced puddling (ReP) plots but wheat yield was highest in the direct seeding without puddling (DSWP) plots and was statistically equal to that in reduced puddling (ReP) plots. Lal (1985) [33] reported that for soils with relatively high clay content, there is no obvious advantage in rice yield by puddling over no till method of seed bed preparation. But in medium textured soil, puddling increases grain yield over no till method (Mambani *et al*., 1989) [34]. Varade and Ghildyal (1967) [67] found that dry matter and grain yield of rice were greater under moderate compaction (1.5 to 1.6 Mg/m^3) in lateritic sandy clay loam soil, but subsequent increase in bulk density decreased yield. Ghidyal and Satyanarayan (1969) [19] showed that higher bulk density beyond 1.63 Mg/m^3 not only affected yield adversely but also delayed the plant growth. Sharma and De Datta (1985) [49] observed that puddling significantly increased grains per panicle and plant height and subsequently yield for both clay and clay loam soil by lowering the soil strength at root zone. Sharma *et al*. (1988) [48] reported that the increase of rice yield in shallow and deep puddling over zero tillage was 33 and 28 percent and 66 and 56 percent for clay and clay loam soil, respectively. The increase in grain yield due to increase in plant height, panicle length and root length density and decrease in soil penetration resistance. Sood and Acharya (1991) [61] conducted an experiment on silty clay loam soil with deep ploughing and deep puddling (DP), shallow conventional cultivation and puddling (CP), conventional cultivation and non puddling (CN), compaction after conventional cultivation (CC) and zero tillage without any preparatory tillage (ZT) as the tillage treatments and observed that CC showed significantly higher plant height and number of tillers per hill at all growth stages and higher dry matter accumulation at 30 DAT whereas DP produced higher panicle length and dry matter accumulation at panicles initiation stage in rice. Rath (1999) [41] observed that yield attributing characters and subsequently yield was significantly higher in case of the peg type puddler and compaction after flooding compared to rotary puddler, spade puddling and no tillage in a silty clay loam soil. Low yield in case of rotary blade puddler was attributed to higher hill mortality and greater bulk density of soil leading to lesser root growth.

Effect on post rice crop

A major constraint to the production of dry season upland crops after rice is crop establishment in poorly structured seedbeds. Immediately after wetland rice the soil is still very wet and sowing under these conditions is expected to result in waterlogging and inhibit emergence and root growth. As the puddled layer dries out, soil strength increases rapidly. Hence, crop establishment and root proliferation through the puddled and compacted layers becomes increasingly more difficult.

Rice (*Oryza sativa* L.) is the most important and widely cultivated staple food crop in Asian countries, where it is grown mostly as a manually transplanted crop in puddled soil (Sanchez, 1976) [45]. Field preparation for transplanting rice is an energy-intensive process, and consists of two operations, i.e. pre-puddling tillage or dry tillage and puddling or wet tillage. Puddling, apart from lowering the percolation losses of water by reducing soil hydraulic conductivity, helps in weed control and creation of soft medium for easy transplanting rice seedlings (De Datta, 1981; Sharma and De Datta, 1986; Kirchhoff *et al*., 2000) [12, 50, 25]. The effect of puddling on puddle quality in terms of puddling depth and percolation rate, however, depends on the initial soil conditions created by pre-puddling tillage (Gajri *et al*., 1999) [18]. The impact of puddling on rice productivity varies in accordance with soil characteristics and climate (Kirchhof *et al*., 2000) [50]. The positive effects of puddling on the permeable (coarse-textured) soils of semi-arid regions of South Asia, particularly those of Indo-Gangetic Plain region (IGP), are frequently documented (Sharma and De-Datta, 1985; Yadav *et al*., 2000; Kukal and Aggarwal, 2003) [50, 69, 29]. On the other hand, extensive field studies on fine-textured soils (clay content varying from 41 to 74%) in the Philippines and Indonesia revealed that puddling was not necessary, and could be omitted without any yield loss (Kirchhof *et al*., 2000) [50]. Puddling results in formation of compacted soil layers below the puddled zone on which soil strength increases rapidly as the soil dries, and limits the depth of root exploitation in subsequent crops (IRRI, 1986) [24]. In the rice–wheat (*Triticum aestivum* L.) cropping system (RWS), which is the predominant annual crop rotation of South Asia occupying nearly 13.5 million ha area in the IGP of India, Pakistan, Bangladesh and Nepal, results are inconsistent regarding the effect of puddling in rice on the yield of a subsequent wheat crop. Whereas some studies suggested a reduction in wheat yields in post-rice soils due to puddling induced changes in soil physical properties (Boparai *et al*., 1992; Fujisaka *et al*., 1994; Dwivedi *et al*., 2003; Singh *et al*., 2005) [8, 16, 14, 57].

The destruction of soil aggregates (or soil structure) and formation of a hardpan during puddling have adverse effects on the yield of subsequent non-rice crops in rotation, and these crops also require more energy for field preparation (Fujisaka *et al*., 1994; Kumar and Ladha 2011) [16, 31]. Another consequence is that the soil infiltration rates in the wheat season are less where the land had been puddled for rice than when the soil had been dry-drilled or kept under no-tillage (Singh *et al*., 2011) [59].

Destruction of aggregates and excessive moisture in rice field often hampers in seedbed preparation and delayed growing of *Rabi* crop and results in poor yield. Where there is sufficient irrigation water to grow rice all the year, this does not matter. However, where there is insufficient water to maintain flooded conditions in the dry season (DS), the soil conditions created by puddling make it difficult to grow a dryland crop during the DS using moisture stored in the soil profile (De Datta, 1981) [12].

Although puddling helps in weed management and reducing water loss through percolation nonetheless it deteriorates the soil environment for post-rice crops (Sharma and De Datta, 1985) [45]. This results in erratic stand establishment of post-rice crops owing to poor contact of seed with soil. Subsurface compaction of soil, caused by puddling, may induce the drought to post- rice crops by restricting the root development (Kirchhof *et al*., 2000) [25]. Bhadoria (1987) [4] from West Bengal observed less seedling emergence of subsequent wheat crop under puddled soil because of more clods of larger size. Bajpai and Tripathi (2000) [2] from Uttar Pradesh reported that the puddling in rice enhanced the root length

density by 12 per cent but later affected adversely the wheat crop and minimized the root length density by 28 per cent. *Rabi* tillage by MB ploughing twice and rototilling twice increased the yield of toria over farmer's practices. Excessive moisture condition of field just after harvest of rice caused difficulty in tillage operation in time and delayed the sowing of *Rabi* crop till second week of December in all the years resulting in poor yield (Barua *et al*., 2007) [3]. Kirchhof *et al*. (2000) [25] reported that different puddling intensities had no significant effect on mungbean and peanut yields whereas increasing puddling intensity decreased soybean yield. They also investigated the effect of the length of the period between rice harvest and sowing of the dry season legume and observed that increasing delay of sowing following rice harvest tended to decrease yields of dry season legumes. This was probably due to very poor soil physical conditions of the Vertisol soil under dry conditions. The reason for the decrease appears to be associated with excessive drying after sowing.
Observation on the interaction between tillage and delay in sowing were investigated by Kirchhof *et al*., (2000) [25] and found that tillage increased yield and the yields were extremely low and uneconomical. The tillage conducted early (1 week) after rice harvest had no effect on yield, while tillage conducted a week later increased mung bean yield. However, the peanut yielded higher when the soil was cultivated. This might be associated with the better physical conditions (lower bulk density) for pod development.

Conclusion

- Continuous inclusion of lowland puddled rice in a cropping sequence year after year results in the development of hard subsurface layers, which act as a hydraulic barrier and impede water movement.
- Water retention in puddled soils is always higher than the non-puddled soil. However, when the submerged puddle soils revert back to upland non-puddle condition, its water retention falls.
- Crop establishment was shown to be the most limiting factor for post-rice crop production followed by the extraction of soil water, which is a function of root growth.
- Puddling is needed only to the required level that improved growth of rice and will also deteriorate less the soil physical condition as compared to more intense puddling.
- Breakdown of hard pan by deep ploughing after every 3-4 years for better post rice crop.
- Post rice crops with the ability of their roots to penetrate hard sub soils would better explorer of available soil water.
- Nutrient and microbial deficiencies of puddled soil correction could be done by proper fertilization, application of organic matter and bio-fertilizers for better post rice crops.
- Sufficient rice straw should be incorporated to the plough layer to maintain soil organic carbon and then to improve soil puddle ability and the recovery of pore structure with wetting and drying cycles.
- Adoption of low water requiring SRI and aerobic rice cultivation system may be an alternative to existing puddled rice system for efficient growing of post rice dry season crops.
- The prospects of growing another crop after puddled rice requires systematic study on tillage of rice crop and its effect on post rice crops.

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