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Acid Soil Amelioration with Paper Mill Sludge and its Impacts on Biomass, Grain Yield, Water Footprints and Nutrient Uptake by Rainfed Groundnut

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Acid soils affect nutrient uptake, water footprints and nitrogen use efficiency directly or indirectly by influencing the availability of plant nutrients, crop growth, biomass and yield. Thus, the maintenance and management of acid soils are very much important to obtain higher productivity and in turn to reduce water footprint of the crop on sustainable basis. In this study, possibility of using low cost liming materials like paper mill sludge (PMS) to ameliorate acid soil was investigated and its impacts on productivity, farm level water footprint and nutrient uptake of groundnut were assessed under tropical monsoon climate of eastern India. The PMS used in this study contained 32.5% calcium carbonate which was applied at different rates *viz.,* 20, 30, 40, 50 and 60% of lime requirements (LR), 4-5 weeks before sowing of the crop and results were compared with the control (no lime treatment, 0% LR). The PMS was found to be useful to enhance the soil pH, nutrient uptake, biomass, leaf area and yield and reduced water footprints of groundnut production significantly when it was applied up to 50% LR. However, no significant differences on these parameters were observed when PMS was applied above 50% LR.

Key words: Water footprints, groundnut, acid soil, paper mill sludge, lime requirements

In eastern India, groundnut is mainly (80% of total groundnut production) grown during rainy season on light textured upland. But growth, biomass and productivity of groundnut on such land is low (850 kg ha^{-1}) due to acidic soil with very low cation exchange capacity (CEC) and low levels of available nutrients. Hence, the resource use efficiency of the crop on such soil is low. Acidic soil environment (pH < 6.5) affects plant growth directly or indirectly by influencing the availability of plant nutrients, particularly phosphorus (P), secondary nutrients (Ca and Mg) and micronutrients (Mo, B and Zn), reducing microbial activity and creating toxicity of Fe and Mn (Al in some cases) (Sumner *et al.* 1991; Sumner and Noble 2003). The maintenance and management of acid soils are thus very important to obtain higher resource use efficiency and productivity of the crop on sustainable basis (Bolan *et al.* 2003; Anetor and Ezekiel 2007; Brown *et al.* 2008; Caires *et al.* 2008). Lime increases soil pH, improves availability of plant nutrients and crop growth, increases nutrient uptake, stimulates biological activity, decreases extractable Al^{3+} and reduces toxicity of some elements (Moschler *et al.* 1973; Wildey 2003). Limestone is the most common liming material used to ameliorate acid soil, but small and marginal farmers of eastern India could not afford to purchase lime in the form of pure $CaCO_3$ or $MgCO_3$ because of their relatively high cost. Alternative cheap sources of liming material like paper mill sludge (PMS) from by-products of paper mill that contains $CaCO_3$ can be used to ameliorate acid soil (Torkashvand *et al.* 2010; Kar *et al.* 2010). However, the quantity of PMS required depends on the paper manufacturing processes, soil type, crop species and cultivars (Noble and Hurney 2000; Caires *et al.* 2005).

With rapid population growth and rising expectation of better life there will be ever increasing demand of water for competing sectors like domestic, industrial and agricultural needs. Since in agriculture, about 85% of global consumptive freshwater is used, water footprint of crops under different management systems can be an important indicator to use water most efficiently under a particular agricultural management system. Water footprints indicate direct (the green and blue water footprint) and indirect (grey water footprint) appropriation of freshwater resources

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and lower water footprint from a crop management system reflects its efficiency to produce more biological yield with less amount of water (Postel *et al.* 1996; Hoekstra 2003; Hoekstra and Chapagain 2008). Many earlier works (Seckler *et al.* 1998; Chapagain and Hoekstra 2004; Hoekstra and Chapagain 2007) have computed water footprints of crops on larger scale (world, continents or countries as a whole). More recently, although a few studies have separated global water consumption for crop production into green and blue water with a better spatial resolution (Rost *et al.* 2008; Siebert and Doll 2008, 2010; Liu *et al.* 2009; Liu and Yang 2010; Hanasaki *et al.* 2010; Fader *et al.* 2011), farm level water footprints information of many crops under different management practices are lacking. In this study, we attempted to improve farm level water footprints of groundnut crop after ameliorating acid soils with different doses of PMS.

Despite, sporadic work was carried out on soil amelioration with PMS and its impacts on crop growth, productivity and nutrients uptake in different parts of the world (Flower 1999; He *et al.* 2009), there is a paucity of information on suitable application rates of PMS and its effects on soil properties, crop productivity and nutrient uptake by groundnut under high rainfall (about 1500 mm annual rainfall), tropical monsoon climate of eastern India. Hence, the objective of this study was to evaluate the impacts of different application rates of PMS on biomass, yield, water footprints and nutrient uptake by groundnut in upland acid soils of the region.

Materials and Methods

Study Area

On farm trial was carried out during 2007 to 2009 rainy seasons in a representative acid soil areas of eastern India (Bhimda, Badasahi block, Mayurbhanj district, Orissa) (Longitude: 86°44′; Latitude: 21°57′). About 80% of the farm families of the area are marginal/small with an average holding size of less than 2 ha. The climate of the study area in general is hot-humid and tropical monsoon type. The mean maximum temperature of 42 °C occurs in the month of May and minimum temperature occurs in December with the value being 8 °C. The mean annual rainfall of the region is 1590 mm, out of which about 80% occurs due to southwest monsoon (June to September) in rainy season. During this season, farmers of the region mostly grow groundnut in rainfed uplands which are acidic in nature (pH ranged from 4.9 to 5.1), but receive very low levels of productivity from the crop.

Treatments and Crop Management

The groundnut crop cv. 'TMV-2' was sown in 3 years on 28th June 2007, 25th June, 2008 and 1st July 2009 keeping the plant to plant distance of 0.15 m and row spacing of 0.30 m, following standard package of practices. Nitrogen, P and K were applied at of 20, 50 and 50 kg ha^{-1} in the form of urea, single superphosphate and muriate of potash, respectively. Six treatments *viz.,* No PMS (0% LR); PMS @ 20% LR (20% LR); PMS @ 30% LR (30% LR); PMS @ 40% LR (40% LR); PMS @ 50% LR (50% LR); PMS @ 60% LR (60% LR) were imposed in randomized block design (RBD) with 3 replications. The PMS was applied every year in ploughed layer, 4-5 weeks before sowing of the groundnut crop. The crop observations like date of occurrence of important phenological stages, biomass, leaf area index, yield and yield components, as influenced by different rates of PMS, were recorded.

Plant samples were collected from five plants at important phenological stages for leaf area index and biomass analysis. A developmental stage was recorded when 50% of the plants in a given plot were reached at that stage. To determine dry biomass production, the samples were oven dried for 48 h at 80 °C in order to stop enzymatic reactions and to remove moisture. The crop was harvested after attaining full maturity and harvesting was done from the central rows for analysis of pod and grain yield.

The leaf area was measured using the following relationships.

$$\text{Leaf area index (LAI)} = \frac{\text{Sum of the leaf area of all leaves}}{\text{Ground area of field where the leaves have been collected}}$$

Soil Sampling and Analysis

Initial soil properties (0-0.15, 0.15-0.30 and 0.30-0.45 m soil depths) of experimental field before starting were analyzed. The soil samples at 0-0.20 m depth were also collected from each treatment in each season before harvesting of the crop to assess the change in soil physicochemical properties after application of PMS. The samples were air-dried and ground to pass through a 2-mm sieve for analyzing their physical properties like texture, soil water retention using standard procedure. The bulk density and saturated hydraulic conductivity of soils were determined using sampler. The chemical properties like soil organic carbon, available macronutrients (N, P and K), pH, EC were estimated using standard procedures (Jackson 1973). Particle size distribution (clay, silt and sand content) was determined by the Hydrometer method. The active acidity *i.e.* pH in water of the soil samples, was determined using a digital pH meter at the soil: water ratio of 1: 2.5 (Jackson 1973). The CEC was determined following the neutral 1 *N* ammonium acetate method (Black 1965). Organic carbon was determined using Walkley and Black (1934) method, available N by alkaline potassium permanganate method. Available P and K were estimated by Bray and Kurtz (1945) extraction method and neutral 1 *N* ammonium acetate method, respectively. Exchangeable Al^{3+} (KCl exchangeable acidity) was determined by titrating the sample with 0.025 *M* NaOH, whereas, Ca^{2+} and Mg^{2+} were determined by titrating the sample with 0.025 *M* EDTA. Exchangeable acidity, base saturation and exchangeable H^+ were determined following the method of Hesse (1971). The lime requirement of surface soils (0-0.15 m) was determined using Shoemaker *et al.* (1961). Plant samples were analyzed for N by micro-Kjeldahal method (Jackson 1973) and N uptake was calculated by multiplying dry matter with N content (%) of plant (Ombo 1994). The P and K in plant samples were analyzed after digestion with di-acid (HNO_3 : $HClO_4$ in the ratio of 10:4) by vanadomolybdo phosphoric yellow colour method and flame photometer, respectively. The chemical and physical properties of the applied PMS were also analyzed using standard procedure (Jackson 1973). The PMS in this study had pH (1:2.5) 8.23; EC 0.20 dS m^{-1}; average Ca and Mg 7.2 cmol(p^+)kg^{-1} soil, $CaCO_3$ equivalent 30%, organic carbon 25%; total N 0.87%, P 0.20%, K 0.14% and Na (water extract) 0.10%.

Crop Evapotranspiration and Seasonal Crop Water Use

The actual crop evapotranspiration (ETa, mm day^{-1}) or crop water requirements depends on climatic parameters (which determine potential evapotranspiration), crop characteristics and soil water availability were derived as per the following standard relationship (Allen *et al*. 1998):

$$ET_a = K_c \times ET_o$$

where, K_c is the crop coefficient and ETo is the reference evapotranspiration (mm day^{-1}). The reference evapotranspiration was computed using Penman-Monteith equation (Allen *et al.* 1998) for limited weather data. The K_c values at different growth stages were obtained from FAO Guideline No. 56 (Allen *et al.* 1998) to compute crop water requirements. USDA SCS method (the method of the United States Department of Agriculture, Soil Conservation Service) was used to compute effective rainfall.

Computation of water footprints

Water footprints is expressed as the volume of water consumed or evaporated and/or polluted to grow a crop per unit mass of economic yield, usually the unit is expressed as $m^3\ t^{-1}$ or L kg^{-1} (Hoekstra 2003). Water footprints of the crop ($m^3\ t^{-1}$) were thus calculated by dividing the total volume of blue, green or grey water use or evapo-transpired ($m^3\ yr^{-1}$) with the quantity of the grain yield of the crop (t yr^{-1}). The total water footprint (WF_{total}) of the crop is the sum of the green (WF_{green}), blue (WF_{blue}), and grey (WF_{grey}) components of water footprints.

Blue water refers to the amount of irrigation water required from stored surface water or renewable groundwater sources to meet the deficit of crop water requirements for achieving potential crop evapotranspiration (PETc) and evaporation during land preparation / land soaking to grow a crop successfully. Thus, blue water requirement/ (ET_{blue}) or the irrigation requirements (IR) is equal to the crop water requirements (CWR, mm) minus effective rainfall ($P_{eff,}$ mm) and profile stored soil moisture contribution (PSMC, mm).

The blue water footprint (WF_{blue}) refers to the volume of blue water consumed ($m^3\ ha^{-1}$) during the life cycle of a crop to the quantity of economic crop yield (t ha^{-1}) produced.

$$WF_{blue}\ (m^3\ t^{-1}) = \frac{\text{Volume of blue water use } (m^3\ ha^{-1})}{\text{Grain yield of the crop } (t\ ha^{-1})}$$

The green water footprint (WF_{green}) refers to the ratio of loss of green water resources (profile stored soil moisture or rainwater as it does not become runoff) due to evaporation or evapotranspiration during the crop growth period to the quantity of economic crop yield (t ha^{-1}) produced. Thus,

$$WF_{green}\ (m^3\ t^{-1}) = \frac{\text{Volume of green water use } (m^3\ ha^{-1})}{\text{Grain yield of the crop } (t\ ha^{-1})}$$

When no rainfall is received during crop growth period, effective rainfall component is zero, but stored profile residual soil moisture of rainy season (PSMC) may serve as a source of green water footprints.

Under unlimited water availability (either through rainfall or irrigation or both sources), the total blue and green water use (WU_{green} + WU_{blue}) are equal to potential crop evapotranspiration (PET) or CWR. When limited water is available, (WU_{green} + WU_{blue}) would be equal or less than total crop water requirement (CWR) for the growing season and, hence, CWU will be equal to the actual crop evapotranspiration (AET).

The grey water footprint (WF_{grey}) is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

$$WF_{grey}\ (m^3\ t^{-1}) = \frac{\text{Volume of grey water use } (m^3\ ha^{-1})}{\text{Grain yield of the crop } (t\ ha^{-1})}$$

The grey water footprint is calculated by dividing the pollutant load (PL, in mass/time) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration C_{max}, in mass/volume) and its natural concentration in the receiving water body (C_{nat}, in mass/volume) (Chapagain *et al.* 2006).

$$WF_{grey}\ (m^3\ t^{-1}) = \frac{\text{PL use } (kg\ ha^{-1})}{(C_{max} - C_{nat})\ kg\ m^{-3}\ (t\ ha^{-1})} \times \frac{1}{t\ ha^{-1}}$$

Grey water footprint ($m^3\ t^{-1}$) related to N pollution was calculated by multiplying the fraction of N that leaches or runoff by the fertilizer-N application rate (kg ha^{-1}) and dividing this by the difference between the maximum permissible concentration of N (kg m^{-3}) and the natural concentration of N in the receiving water body (kg m^{-3}) and whole divided by the actual crop yield (t ha^{-1}) Chapagain *et al.* (2006). In this paper, we have taken a flat rate of N leaching equal to 10% of the N application rate and used the permissible limit of 10 mg NO_3^- L^{-1} as per the standard recommended by USEPA (2005) for nitrate in drinking water to estimate the volume of water necessary to dilute leached N to the permissible limit. Natural concentration of N in the receiving water body of the study area was considered nil.

Water requirement for land soaking during land preparation

This is the water required to soak the land prior to the initial breaking of the soil, either by ploughing or by any other means which can be estimated using the following relationship (Ali 2010).

This is expressed as: $WR_{LS} = W_s + C \times ET_O + P - Re$

where, WR_{LS} is the depth of irrigation water required for land soaking (mm), W_s is the depth of water required to saturate the soil (mm), ET_0 is the reference evapotranspiration during the time of soil saturation (mm), C is the evaporation coefficient equating reference evapotranspiration to evaporation rate. The value of C is about 0.9 P is the deep percolation loss during the soil saturation (mm), R_e is the effective rainfall during the period (mm).

Since for water footprints computation we are interested in evaporation loss (E_{LS}) during land preparation,

Thus, $E_{LS} = C \times ET_0$

Based on the available data, it is revealed that 0.66 to 1.2 m^3 and 0.41 to 1.14 m^3 water are consumed during manufacturing process of one quintal of urea and P_2O_5, respectively. In this study average values *i.e.* 0.93 and 0.77 m^3 of water was taken for 1 quintal of urea and P_2O_5, respectively, which were insignificant compared to crop evapotranspiration. Because of paucity of information, water consumed for K-fertilizer was not added.

Statistical analysis

All data were statistically analyzed by standard analysis of variance (ANOVA) technique as per the procedure suggested by Gomez and Gomez (1984). Wherever treatments were found significant based on results of F-test, least square differences (LSD) were calculated using SAS (Statistical analysis system) software (v 9.2).

Results and Discussion

Initial basic properties of the soil profile

The initial soil properties (0-0.15, 0.15-0.30 and 0.30-0.45 m) were analyzed and the soils within the experimental area was found to be relatively homogeneous. Soil texture was sandy loam in nature where clay content varied from 23.8% (0-0.15 m) to 27.3% (0.30-0.45 m) (Table 1). The bulk density was 1.42 Mg m^{-3} at 0-0.15 m depth and at 0.30-0.45 m depth, it became 1.46 Mg m^{-3}. The soil pH was slight to moderately acidic and no salt problem was detected in the soil. The soil organic carbon content ranged from 5.7 g kg^{-1} at upper layer (0-0.15 m) to 4.6 g kg^{-1} at lower depth (0.30-0.45 m). The CEC was 6.95 to 7.18 cmol $(p^+)kg^{-1}$ soil at different depths. The percentage base saturation of the soil was low (41.3 to 44.5%) due to prevalence of low concentration of basic cations. The soils were strong to moderately acidic and pH ranged from 4.9 to 5.1 at different depths. In general, soil was sandy loam, strong to moderately acidic with low organic carbon content. Due to strong to moderate

Table 1. Initial properties of the soil of experimental field at different depths

Soil parameters	Soil depth (m)		
	0-0.15	0.15-0.30	0.30-0.45
Permanent wilting point ($m^3\,m^{-3}$)	0.095	0.098	0.108
Field capacity ($m^3\,m^{-3}$)	0.281	0.295	0.281
Available water capacity ($m^3\,m^{-3}$)	0.156	0.170	0.163
Saturated hydraulic conductivity (cm h^{-1})	24.5	13.2	7.80
Bulk density (Mg m^{-3})	1.42	1.44	1.46
Organic carbon (g kg^{-1})	5.7	4.8	4.6
Clay (%)	23.8	26.3	27.3
Silt (%)	13.4	15.6	18.9
Sand (%)	62.8	58.1	53.8
pH in water	4.9	5.0	5.1
Ca [cmol(p^+)kg^{-1} soil]	2.15	2.19	2.25
Mg [cmol(p^+)kg^{-1} soil]	0.85	0.87	0.88
Na [cmol(p^+)kg^{-1} soil]	0.12	0.14	0.16
Al^{3+} [cmol(p^+)kg^{-1} soil]	1.25	1.20	1.22
CEC [cmol(p^+)kg^{-1} soil]	6.95	7.05	7.18
Base saturation (%)	42.9	41.3	44.5
Exchangeable acidity (%)	43.6	44.6	44.9

acidity and poor nutrient availability, the productivity of crop on such soils was not optimum. Hence, it is necessary to ameliorate the soils with lime materials like pure $CaCO_3$, CaO, paper mill sludge, press mud *etc.* to increase the soil pH and nutrients uptake.

Impact of PMS on dry biomass and leaf area index

The effects of different doses of PMS in different study years on grain weight, pod weight, haulm weight and total biomass are presented in figures 1a and 1b, respectively. Dry matter yield increased significantly *(P < 0.05)* in the PMS treated plots from 0% LR to 50% LR. Total biomass (pod yield + haulm yield) of 4076, 4269, 4523, 4850, 5359 and 5455 kg ha^{-1} was obtained under 0% LR, 20% LR, 30% LR, 40% LR, 50% LR and 60% LR, respectively. Application of 60% LR produced greater total biomass, but not significantly different from 50% LR. With regard

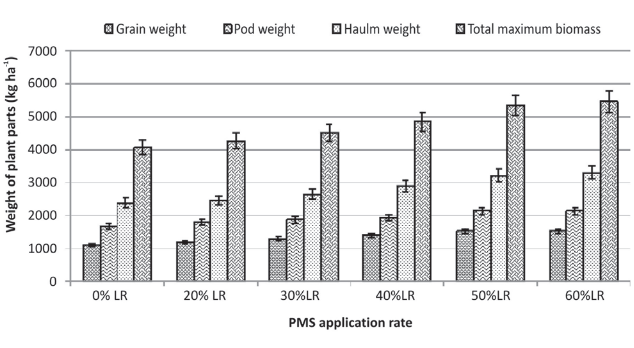

Fig. 1a. Grain weight, pod weight, haulm weight and maximum biomass production under different PMS application rates

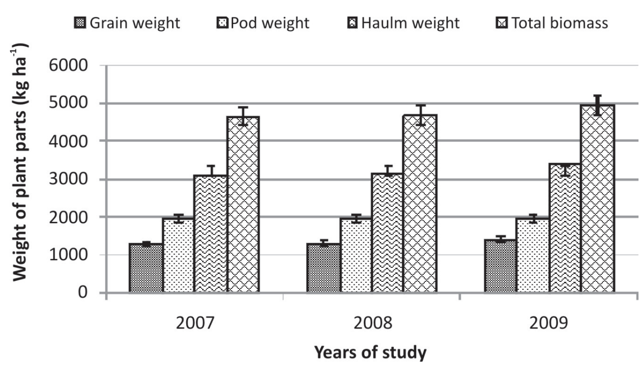

Fig. 1b. Grain weight, haualm weight and maximum biomass production in different study area

to effects of years on total biomass production, no significant differences were observed between first and second years, but in the third year significantly higher biomass was achieved. The peak LAI of 3.61, 3.80, 4.32, 4.61, 4.83 and 5.06 were recorded under 0% LR, 20% LR, 30% LR, 40% LR, 50% LR, 50% LR and 60% LR, respectively (Fig. 2a). The years had no significant effects on peak LAI production (Fig. 2b). Yield components of the crop were also influenced by PMS doses and years of study (Table 3). Like biomass, application of 60% LR produced higher yield but not significantly different from 50% LR. With, regard to effects of years on productivity of the crop, no significant difference in grain yield was observed between first and second years, but in the third year significantly higher grain yield was achieved. This might be due to the significant improvement in soil pH.

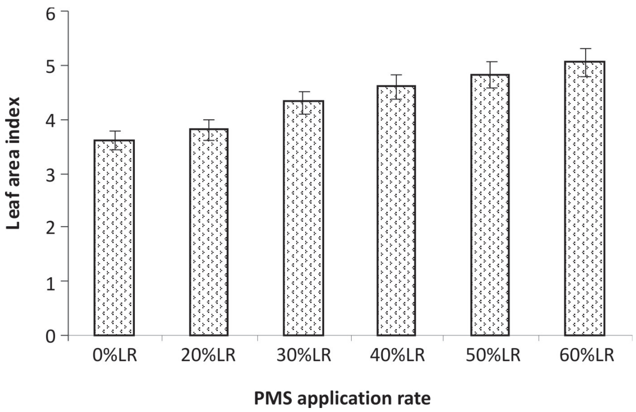

Fig. 2a. Peak leaf area index as influenced by paper mill sludge application rates

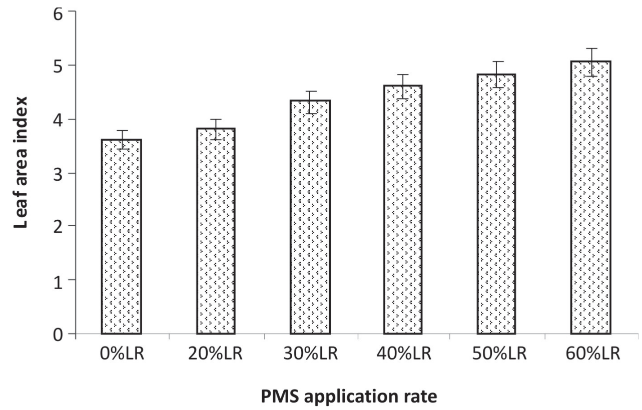

Fig. 2b. Peak leaf area index in different years of study

Grain Yield, Crop Water Requirement and Water Footprints

The crop water requirements, effective rainfall and water footprints of the crop of different study years were computed as per the methodology and are presented in table 2. The crop water requirements of 405, 410 and 398 mm were computed in 2007, 2008 and 2009, respectively. The effective rainfall was computed as 764, 658 and 674 mm in three respective study years. Since, effective rainfall was more than that of crop water requirement in all three study years, no irrigation was applied to the crop. Study revealed that there was significant effect of different doses of PMS on yield and yield attributes of groundnut. Average over years, the lowest grain yield (1063 to 1126 kg ha^{-1}) was obtained under 0% LR whereas, the high-

Table 2. Crop yield and water footprints as affected by PMS doses and years of study

Paper mill sludge doses (PMS)	Grain yield (kg ha^{-1})	WRls (mm)	PETc (mm)	ER (mm)	Water–Fertilizer (m^3)	Green + Blue WF (m^3 t^{-1})	Grey WF (m^3 t^{-1})	Total WF (m^3 t^{-1})
			First Year (2007)					
0% LR	1063^{e}	48.5	405	764	0.791	4267	1.88	4268
20% LR	1166^{d}	48.5	405	764	0.791	3890	1.72	3891
30% LR	1238^{c}	48.5	405	764	0.791	3663	1.62	3665
40% LR	1317^{b}	48.5	405	764	0.791	3444	1.52	3445
50% LR	1483^{a}	48.5	405	764	0.791	3058	1.35	3060
60% LR	1493^{a}	48.5	405	764	0.791	3038	1.34	3039
Mean	1293	48.5	405	764	0.791	3508	1.55	3509
			Second Year (2008)					
0% LR	1073^{e}	48.5	410	658	0.791	4273	1.86	4275
20% LR	1163^{d}	48.5	410	658	0.791	3943	1.72	3944
30% LR	1288^{c}	48.5	410	658	0.791	3560	1.55	3562
40% LR	1367^{b}	48.5	410	658	0.791	3354	1.46	3356
50% LR	1479^{a}	48.5	410	658	0.791	3100	1.35	3102
60% LR	1496^{a}	48.5	410	658	0.791	3065	1.34	3067
Mean	1311	48.5	410	658	0.791	3498	1.53	3499
			Third Year (2009)					
0% LR	1126^{e}	48.5	398	674	0.791	3966	1.78	3967
20% LR	1246^{d}	48.5	398	674	0.791	3584	1.61	3585
30% LR	1362^{c}	48.5	398	674	0.791	3279	1.47	3280
40% LR	1522^{b}	48.5	398	674	0.791	2934	1.31	2935
50% LR	1603^{a}	48.5	398	674	0.791	2786	1.25	2787
60% LR	1618^{a}	48.5	398	674	0.791	2760	1.24	2761
Mean	1413	48.5	398	674	0.791	3160	1.42	3162

The values in the column followed by same letters are not significant at 5% probability as per the Duncan's Multiple Range Test (DMRT).

est grain yield of 1493 to 1618 kg ha^{-1} was obtained under 60% LR, though it was statistically non-significant from the yield obtained at 50% LR. By applying PMS @ 20% LR, grain yield was increased by 10.1 to 18.1% over no PMS in different study years. On the other hand, the grain yield was increased by 47.1, 58.1 and 67.2% under 60% LR over 0% LR in the first, second and third years, respectively but in every year no significant differences in grain yield were observed between 50% LR and 60% LR.

Water footprints (WF) of the crop *i.e.* volume of green, blue and grey water consumed to raise the crop per unit mass of economical yield were higher when the soil was not ameliorated with PMS which might be attributed to low grain yield obtained on acid soils. The WFP reduced significantly in all study years with increased dose of PMS from 20% LR to 50% LR due to significant yield enhancement in these PMS treated plots. The highest WFP was observed when no PMS was applied with the values being 4268, 4275 and 3967 m^3 t^{-1} in 2007, 2008 and 2009, respectively. On the other hand, lowest WFs of 3039, 3067 and 2761 m^3 t^{-1} were achieved under 60% LR in three respective study years. Since effective rainfall was more than that of the crop water requirements, entire WF was contributed by green water footprints and WF contribution from blue water was nil. The crop was also grown with good quality water, as a result the grey WF was nil. With PMS application at 20% LR, WF of the crop was reduced by 16.2, 18.7 and 25.8% in 2007, 2008 and 2009, respectively, compared with 0% LR. The WF was reduced by 27.8 to 36.6% under 60% LR and 26.6 to 36.3% under 50% LR, which were similar. Thus, it is inferred that application of liming material in the form of PMS has the potential to enhance the yield and to reduce WF of groundnut production in acid soil. Average across the soil management treatments, WFs of 3509, 3499 and 3162 m^3 t^{-1} were obtained in the first, second and third years, respectively. The study also suggests that the water footprint of a crop to a large extent is influenced by agricultural management rather than by the agro-climate under which the crop is grown. This provides an opportunity to improve yield and water productivity through different improved agro-management practices to reduce water footprints. The yield attributes of the crop under different PMS doses and in different study years are also presented in table 3. Yield attributes showed the similar trend as in the case of grain yield.

Impact of PMS on soil pH, organic carbon and available water capacity

The crop growth and productivity were enhanced after addition of PMS to the soils. This might be attributed to improve soil physicochemical properties (Table 4). Soil pH is a very important property because it determines the availability of nutrients, soil microbial activity and various soil physicochemical processes. An upward shift in pH was noticed from 4.9 (control) to 6.2 (0.6 LR treatments) in the 0-0.15 m depth. Increase in pH was 0.40 units for L_2, 0.70 units for L_3, 0.9 units for L_4 and 1.1 units for L_5 and 1.3 for L_6 compared to the control (L_0). It was also found that PMS significantly increased the pH, which was proportional to the application rate of PMS up to 50% LR (Table 4). Organic carbon contents of different rates of PMS amended soil were 5.4 to 6.1 g kg^{-1}. Averaged over study years, the organic carbon content was significantly higher under 50 and 60% LR than that of other treatments. But averaged over the PMS treated plots, the impacts of PMS on soil or-

Table 3. Yield components of groundnut as influenced by PMS doses and years of study

Factors	Pod m^{-2}	Grain m^{-2}	1000 grain wt (g)	Shelling (%)	Grain yield (kg ha^{-1})
Doses of paper mill sludge (PMS)					
0% LR	164.3 ^{e}	366.9 ^{e}	296.3 ^{d}	59.9 ^{d}	1087.2 ^{a}
20% LR	174.7 ^{d}	390.2 ^{d}	305.3 ^{c}	62.7 ^{c}	1191.6 ^{c}
30% LR	180.3 ^{c}	420.7 ^{c}	308.0 ^{c}	67.1 ^{b}	1295.8 ^{c}
40% LR	188.3 ^{b}	449.4 ^{b}	312.0 ^{b}	70.8 ^{a}	1402.1 ^{b}
50% LR	199.1 ^{a}	479.2 ^{a}	317.7 ^{a}	71.4 ^{a}	1521.7 ^{a}
60% LR	200.0 ^{a}	482.1 ^{a}	318.7 ^{a}	71.9 ^{a}	1535.9 ^{a}
Years of study					
1st (2007)	183.7 ^{b}	416.8 ^{b}	309.5 ^{a}	65.4 ^{b}	1293 ^{b}
2nd (2008)	184.0 ^{b}	422.0 ^{b}	309.8 ^{a}	66.6 ^{b}	1311 ^{b}
3rd (2009)	185.5 ^{a}	455.3 ^{a}	309.6 ^{a}	69.2 ^{a}	1413 ^{a}

The values in the column followed by same letters are not significant at 5% probability as per the Duncan's Multiple Range Test (DMRT).

Table 4. Impacts of PMS on soil pH, organic carbon and available water capacity

Factors	pH	Organic carbon ($g\ kg^{-1}$)	Available water capacity ($m^3\ m^{-3}$)
Doses of paper mill sludge (PMS)			
0% LR	4.9 ^{e}	5.4 ^{d}	0.158 ^{b}
20% LR	5.3 ^{d}	5.9 ^{c}	0.160 ^{b}
30% LR	5.6 ^{c}	5.9 ^{d}	0.160 ^{b}
40% LR	5.8 ^{b}	6.0 ^{a}	0.164 ^{b}
50% LR	6.0 ^{a}	6.0 ^{a}	0.168 ^{a}
60% LR	6.2 ^{a}	6.1 ^{a}	0.162 ^{a}
Years of study (Y)			
1st (2007)	5.5 ^{b}	5.89 ^{b}	0.161 ^{a}
2nd (2008)	5.6 ^{a}	5.93 ^{b}	0.162 ^{a}
3rd (2009)	5.8 ^{a}	6.01 ^{a}	0.164 ^{a}

The values in the column followed by same letters are not significant at 5% probability as per the Duncan's Multiple Range Test (DMRT).

ganic carbon was not found significant in different study years.

The water holding capacity of the soil was significantly raised by the application of lime sludge under 50 and 60% LR treatments because water retention capacity of PMS was more than that of the soil. But averaged over the PMS treatments, the impacts of PMS on available water capacity in different study years was found to be insignificant. This effect could be ascribed to increase in total porosity of soil on account of altered mechanical composition of the PMS treated soil. Increased water holding capacity of soil upon addition of PMS (up to 50% LR) was likely to provide better soil–water relationship for growing plants.

Impacts of PMS on N, P, K uptake and root nodulation

Paper mill sludge increased N, P and K uptake significantly from 0% LR to 60% LR (Table 5). Highest N uptake of 96.9 kg ha^{-1} was observed under 60% LR and lowest was at 0% LR (62.7 kg ha^{-1}). With the addition of PMS, P uptake also increased significantly due to the higher dry matter yield in PMS treated plots compared with control. Phosphorus is an essential plant nutrient and is indispensable for phospholipids, ATP and nucleic acids synthesis and therefore a deficiency of P can limit plant growth (Schachtman *et al.* 1998). The N and P uptake were not significantly varied between 50% LR and 60% LR, which might be attributed to insignificant increase of plant biomass and yield between these two treatments. Similar trend was also observed in case of K uptake. PMS increased K uptake significantly from 0% LR to 50% LR treatments and this was due to the higher dry matter yield compared with control. Averaged over PMS treatments, N, P and K uptake was not found significantly variable in first and second years, but in the third year, N, P and K uptake was significantly higher.

Impacts of paper mill sludge on the numbers and weight (g/plant) of root nodules in groundnut were also studied. Application of different levels of PMS (20 to 60% LR) increased the number of nodules and their dry weight significantly compared to control (0% LR) (Table 5). The nodule numbers per plant were 18, 22, 26, 28, 30 and 30 under 0% LR, 20% LR, 30% LR, 40% LR, 50% LR and 60% LR, respectively. The nodule weight was also significantly higher under PMS treated plots (20 to 60% LR) than that of the control (0% LR). It might be attributed to better soil physicochemical properties in PMS treated plots,

Table 5. Impacts of PMS on nutrient uptake and root nodulation

Factors	N uptake ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)	K uptake ($kg\ ha^{-1}$)	Nodule number per plant	Nodule weight per plant (g)
Doses of paper mill sludge (PMS)					
0% LR	62.7 ^{e}	11.5 ^{e}	32.7 ^{e}	18 ^{e}	0.117 ^{e}
20% LR	68.6 ^{d}	12.4 ^{d}	36.4 ^{d}	22 ^{d}	0.146 ^{d}
30% LR	77.3 ^{c}	14.1 ^{c}	40.2 ^{c}	26 ^{c}	0.172 ^{c}
40% LR	82.7 ^{b}	15.1 ^{b}	42.3 ^{b}	28 ^{b}	0.193 ^{b}
50% LR	95.8 ^{a}	17.1 ^{a}	47.5 ^{a}	30 ^{a}	0.224 ^{a}
60% LR	96.9 ^{a}	17.4 ^{a}	47.7 ^{a}	30 ^{a}	0.231 ^{a}
Mean	80.6	14.61	41.1	25.6	0.181
Years of study					
1st (2007)	74.6 ^{b}	13.5 ^{b}	39.8 ^{b}	24.0 ^{a}	0.167 ^{b}
2nd (2008)	74.8 ^{b}	13.5 ^{b}	38.9 ^{b}	25.9 ^{a}	0.186 ^{a}
3rd (2009)	79.0 ^{a}	14.7 ^{a}	41.0 ^{a}	26.3 ^{a}	0.193 ^{a}
Mean	76.1	13.9	39.9	25.4	0.182

because survival of microorganisms depends largely on active and reserve acidity and CEC of the soil. As a result, the activities of microorganisms increased after neutralizing the soil solutions with PMS. Similar observations were also obtained by Ghosh (2003), Gogoi *et al.* (2003) and Salam *et al.* (2004).

Conclusions

The application of PMS was found to be useful to enhance the soil pH and nutrient uptake, biomass, leaf area and yield and in turn it reduced water footprints of groundnut production significantly. The increased soil pH after amendment with PMS may be attributed to the presence of Ca, Mg and Na in PMS. The nutrient uptake, crop growth and productivity enhanced up to PMS application rate of 50% LR, but there were no significant effects on growth and productivity of the crop when PMS was applied above 50% LR. This, however, needs further studies with various crops to determine the correct rates and to study the residual and environmental impact of application of this material to the soil. Water footprints (WF) of the crop were significantly reduced with increased dose of PMS and, thus, it is concluded that WF of the crop to a large extent is influenced by agricultural management rather than by the agro-climate under which the crop is grown. This provides an opportunity to enhance yield and water productivity through improved agro-management in order to reduce WFs.

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