J. Jpn. Soc. Soil Phys.
土壌の物理性
No. 141 p.3 ～ 18 (2019)

論　文
Original Paper

Effects of soil amendments on pH and aggregate stability of saline sodic soil and acid sulfate soil in Mekong delta, Viet Nam

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Abstract: Acid sulfate soils and salt-affected soils are widely distributed in the Mekong Delta of Viet Nam. As well as the improvement of chemical properties, it is essential to minimize soil structural degradation. However, relatively little research has been conducted on behaviors of aggregates in the Mekong Delta. In the present study, saline and sodic soil (SS), alluvial soil (AS), and acid sulfate soil (ASS) were collected from the Mekong Delta. First, aggregate stability tests were conducted on them. Base on the aggregate stability test, dry clods of 2–5 mm in size under fast wetting process were used to evaluate aggregate stability of the soils after incubation with soil amendments. Chicken manure was used as a compost and eggshell-$CaCO_3$ was an alternative for lime. Soil and amendments were mixed and incubated in a glass bottle for 45 days at a constant temperature of 25 °C. During the incubation, CO_2 concentration in the headspace of the glass bottle was periodically measured. After incubation, soil pH and aggregate stability were evaluated. Mean weight diameter (MWD) was used to evaluate aggregate stability. Eggshell application increased the pH of all three soils. Compost raised the pH of SS and AS but it was less effective at raising pH of ASS. The combination of compost and eggshell was the most effective at increasing soil pH. Rapid increases in CO_2 emission rate after eggshell application suggested that the $CaCO_3$ rapidly reacted with the H^+ in the soils. Correlations between soil pH and CO_2 emission suggested that microbial activity increased with increasing in soil pH. Eggshell application alone destabilized soil aggregates, whereas the compost and the compost-eggshell combination improved aggregate stability.

Key Words : soil improvement, soil structure, chicken manure compost, eggshell, soil deterioration

1. Introduction

Approximately 65 % of the land in the Mekong Delta of Viet Nam is used for agriculture (General Statistics Office of Vietnam, 2015). However, salt-affected soil and acid sulfate soil prevalent there are reducing crop yields. Salt-affected soil has increased from 0.7 million ha to 0.88 million ha between 1975 and 2005 (Duc and Dao, 2011) and increased to 1.4 million ha in 2011 (Viet Nam-Netherlands Cooperation, 2011). Acid sulfate soils (ASS) decreased from 1.8 million ha to 1.5 million ha between 1975 and 2005 (Duc and Dao, 2011) and further declined to 1 million ha by 2011 (Viet Nam-Netherlands Cooperation, 2011). To ensure food security for rapidly growing populations, it is imperative to sustain soil productivity through proper agricultural practices.

Acid sulfate soil (ASS) is formed by the oxidation of pyrites (FeS_2) in the soil. Sulfuric acid (H_2SO_4) is one of the end products in pyrite oxidation, and it lowers soil pH (Attanandana and Vacharotayan, 1986). At a depth of 0–100 cm, the pH range of ASS is from 2 to 4 (Attanandana and Vacharotayan, 1986; Minh and Tri, 2006). When the pH < 4.0, the soluble forms of aluminum ion (Al^{3+}) and ferric ion (Fe^{3+}) are abundant in the soil. The release of hydron (hydrogen ion, H^+) from soluble Al^{3+} and Fe^{3+}hydrolysis reduces pH of ASS (Iqbal, 2012; Strawn et al., 2015; Stefansson, 2007).

Saline and sodic soils (SS) have both high salinity and sodicity. They are classified on the basis of the electrolyte conductivity of their saturation extracts (ECe) ($>$ 4 dS m^{-1}), pH (< 8.5), and exchangeable sodium percentage (ESP) (> 15 %) (USSL Staff, 1954). The soil structure of SS is fragile and susceptible to structural degradation. High ESP increases clay dispersion (Abu-Sharar et al., 1987). Clay particles disperse by the expansion of the diffuse double layer around the particles (Shainberg and Letey, 1984; Abu-Sharar et al., 1987). Dispersed clay plugs soil pores and reduces soil hydraulic conductivity (Frenkel et al., 1978; Farahani et al., 2018).

Soil productivity is also affected by aggregate stability.

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2018 年 6 月 27 日受稿　2018 年 11 月 30 日受理

Stable soil aggregates support nutrient cycles, water and gas movement, and root respiration. Aggregate stability is influenced by aggregate breakdown processes like fast wetting, slow wetting, and mechanical breakdown (Le Bissonnais, 1996). Slaking by entrapped air occurs when dry soils exposing to the fast wetting process. It corresponds to the cases of sudden water application such as border and furrow irrigation to dry soils. In the slow wetting process, water is gradually supplied to the soil, differential swelling and physicochemical dispersion predominate aggregate breakdown. Raindrop impact is a mechanical action which can contribute to aggregate breakdown.

To make a good seedbed, 2–4 mm clods are recommended to create by tillage (Braunack and Dexter, 1988). However, farmers often tend to till too much to make smooth seedbed surface. In the study of Legout et al. (2005), aggregates were less stable in the initially < 3 mm clods than in the initially 3–5 mm, 5–10 mm, and 10–20 mm clods.

Aggregate stability is affected by initial soil moisture conditions, too. Aggregate stability increases with increase in initial soil water content prior to immersion to water (Kemper and Rosenau, 1984). Under fast wetting process, initially moist aggregates of 2–4.75 mm in diameter were more stable than initially dry aggregates of the same size (Almajmaie et al., 2017). The relatively smaller volumes of entrapped air in initially moist aggregates may produce less compression force under fast wetting than in initially dry aggregates (Kemper and Rosenau, 1984; Vermang et al., 2009). Therefore, breakdown processes and initial conditions must be considered for aggregate stability analysis.

Liming is a common measure to increase pH of acid soils. The pH increased from 5.1 to 5.6, 5.9, 6.4, and 6.8 in response to $CaCO_3$ application rates of 0.75, 1.5, 3.0, and 4.0 g $CaCO_3$kg-soil^{-1}, respectively (Whalen et al., 2002). When the $CaCO_3$ application rate increased from 4.0 to 10.13 g $CaCO_3$ kg-soil^{-1}, pH of the acid sulfate soil increased to 4.51 and 6.10, respectively, from its initial, 3.19 (Khoi et al., 2010). However, liming may have adverse effects on soil structure. Liming increased clay dispersion and decreased the infiltration rate of a Brazilian Oxisol 6 weeks after application (Roth and Pavan, 1991). The effects of liming on aggregate stability of acid sulfate soil are not clear.

Compost improves soil fertility (Dikinya and Mufwanzala, 2010), enhances soil pH (Whalen et al., 2002), and stabilizes soil aggregates (Wortmann and Shapiro, 2008). Whalen et al. (2002) reported that the pH of an acidic soil increased from 5.1 to 6.2 after compost was applied at the rate of 40 g kg soil^{-1} as dry matter. The pH of an acid sulfate soil rose from 3.19 to 4.16 with the addition of 62.5 g compost kg soil^{-1} and to 6.42 when 62.5 g compost kg soil^{-1} with 10.13 g $CaCO_3$ kg-soil^{-1} was applied (Khoi et al., 2010). The pH rise after compost application was explained by Al-organic matter complexes (Naramabuye and Haynes, 2006a). This leaded to a reduction of soluble Al^{3+}concentration by adding compost (Khoi et al., 2010). Yan et al. (1996) reported the role of decarboxylation of organic anions on the pH rise. Khoi et al. (2010) reported rise in NH^{4+}-N and NO_3^--N was a contributor of micro-organism activity after compost application with or without $CaCO_3$ to the acid sulfate soil. However, they did not have the evidence of increase in micro-organism activity in acid sulfate soils after the either compost or combinations of compost and $CaCO_3$. In addition, they did not consider aggregate stability of acid sulfate soil after the amendment application, neither.

The beneficial effects of organic matter on aggregate stability of sodic soil were reported by Quirk and Murray (1991) and Nelson and Oades (1998). Aggregate stability of saline sodic soil was improved by adding compost at 75 t ha^{-1} (Chaganti et al., 2015). Products from decomposition of organic matter help to form stable aggregates. Micro-organisms decompose organic matter and release monosaccharides and/or polysaccharides which bind soil particles and re-form soil aggregates (Griffiths and Jones, 1965; Tisdall and Oades, 1982). Microbial activity during this process can be evaluated by CO_2 emission rate. Soil physico-chemical properties and amendment inputs influenced microbial activity. After 17 weeks incubation, soil CO_2 respiration of acid soils subjected to a combination of lime and litter was higher than that of acid soils added with either lime or litter (Condron et al.,1993). The rise in pH of acid soil in response to liming increased carbon mineralization from microbial activity and reduced aggregate stability in the long term (Karcauskiene et al., 2015). It is unknown about the effects of compost and $CaCO_3$ application on changes in CO_2 emission associated with pH and soil aggregate stability in acid sulfate soil. Our hypothesis was that the combined application of compost and $CaCO_3$ is more effective in improving saline and sodic soil and acid sulfate soil than the application of either compost or $CaCO_3$ alone. The objectives of this study were to (1) determine the effects of breakdown processes, initial clod sizes, and initial soil moisture on soil aggregate stability of the soils, (2) discuss the effects of compost and $CaCO_3$ application on pH, CO_2 emission, and aggregate stability of saline sodic soil and acid sulfate soil in the Mekong Delta of Viet Nam.

2. Materials and Methods

2.1 Soil sampling site

Soil samples were collected at three sites in the Mekong

Delta, Viet Nam. Alluvial soil (AS) (Epigleyic Fluvisols: FLglp) (N: 10°06'48.8"; E: 105°30'39.5") sampled at the field has continuously been used for Luffa Gourd growing during seven years. Saline and sodic soil (SS) (Episalic Solonchaks: SCszp) (N: 08°34'40.5"; E: 104°49'10.8") sampled at the field has been no crop during 2 years after soil accretion. Acid sulfate soil (ASS) (Epi OrthiThionic Fluvisols: FLtiop) (N: 09°43'20.3"; E: 105°22'46.8") sampled at the field has been continuously used for pineapple growing during 50 years. They were taken at a depth of 0–20 cm. Soil types were defined according to the map inventory of the Mekong Delta following the World Reference Base for Soil Resources-Food Agriculture Organization of the United Nations at scale of $1/250,000$ (Minh and Tri, 2006) and World Reference Base for soil resources classification systems (ISSS/ISRIC/FAO, 1998). Surface litters and vegetation were removed before the samples were collected. Then, they were packed in plastic bags and transported to the laboratory with minimum disturbance of the natural soil structure.

2.2 Analytic methods of soil properties

Soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was determined from 1 : 5 soil/water extracts (McLean, 1982) using a LAQUAtwin pH meter (Horiba, Kyoto, Japan). $EC_{1:5}$ was determined from 1:5 soil/water extracts (Rhoades, 1996) using a LAQUAtwin EC meter (Horiba, Kyoto, Japan). ECe was derived from the $EC_{1:5}$ and water content at saturation. Percent organic carbon (% OC) and total nitrogen (% N) were determined by dry combustion of the soil at 950 °C by a CN Element analyzer (Vario EL cube, Elementar Analysensysteme GmbH, Langenselbold, Germany). Soluble Ca^{2+}, Mg^{2+}, and Na^{+} were measured in 1 : 5 soil/water extracts using ion chromatograph. To prepare these extracts, 1 g air-dried soil was weighed and mixed with 5 mL distilled water in a 50-mL centrifuge tube. The tube was shaken for 30 min and centrifuged for 10 min at 5600×g. The supernatant was passed through a 0.45-μm filter. The ion chromatograph system consisted of DGU20A, LC20A, LC20AD, SIL10Ai, SCL10A, CDD10A, and CTO20A (Shimadzu corporation, Tokyo, Japan). The columns were Shim-pack IC-A1 (100 mm × 4.6 mm i.d. and 12.5 μm particle size) (Shimadzu Corporation, Tokyo Japan) and Shim-pack IC-GA1 (10 mm × 4.6 mm i.d.) (Shimadzu Corporation, Tokyo, Japan). The sodium adsorption ratio (SAR) was calculated as follows:

$$\mathrm{SAR} = \frac{[\mathrm{Na^+}]}{\sqrt{([\mathrm{Ca^{2+}}]+[\mathrm{Mg^{2+}}])/2}} \tag{1}$$

where SAR is expressed in $(\mathrm{mmol_c\ L^{-1}})^{0.5}$. $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the Na^+, Ca^{2+}, and Mg^{2+}concentrations in soil solution, and are expressed in $\mathrm{mmol_c\ L^{-1}}$. The exchangeable sodium percentage (ESP) was determined from the Gapon formulae:

$$ESR = \frac{K_\mathrm{G}}{\sqrt{1000}} SAR \tag{2a}$$

$$ESP = \frac{100 \times ESR}{1 + ESR} \tag{2b}$$

where K_G is the cation selectivity coefficient and $K_\mathrm{G} = 0.5$ $(\mathrm{mmol_c\ L^{-1}})^{-0.5}$ (Gapon, 1933). ESR is exchangeable sodium ratio. The field capacity was determined by a hanging water table at -100 cm H_2O ($\psi = -10.1$ kPa) (Klute, 1986). The cation exchangeable capacity (CEC) was measured by the ammonium acetate method (Sumner and Miller, 1996). The soil texture was measured by the Robinson pipette method (Gee and Bauder, 1986). The dry bulk density ($\mathrm{g\ cm^{-3}}$) was measured by the undisturbed core method (Grossman and Reinsch, 2002). The pycnometer method was used to determine the soil particle density ($\mathrm{g\ cm^{-3}}$) (Blake and Hartge, 1986). The saturated hydraulic conductivity (K_sat) ($\mathrm{cm\ s^{-1}}$) was measured in saturated soil packed in 100 $\mathrm{cm^3}$ columns using the falling-head method with tap water (Klute and Dirksen, 1986).

2.3 Preparation for aggregate stability test

Soil blocks collected in the fields were cut into pieces smaller than 5 cm in size and left them at room temperature to reduce soil moisture to be proper moisture for handling. All soil sections were cut into square clods of 1–3 mm, 2–5 mm, and 5–10 mm. This process simulated the production of clods by tillage harrowing. The clods were adjusted to two levels of soil moisture, namely, moist and air-dried with water content ~ 50 % and ~ 5 %, respectively. Field wetness and dryness affecting aggregate stability were simulated in the laboratory using moist and air-dried clods.

2.4 Aggregate stability test

Aggregate stability was evaluated by fast wetting, slow wetting, and mechanical breakdown (Le Bissonnais, 1996). The procedures are described in a schematic diagram (Fig. 1). Fast wetting simulates aggregate breakdown caused by rapid soil immersion in water corresponding to heavy rainfall or furrow or border irrigation. Clods were rapidly submerged in 100 mL deionized water for 10 min. Slow wetting simulates aggregate breakdown caused by low-intensity rainfall. Clods were left on a tension table connecting with Mariotte bottle to supply water with a constant pressure of -3 $\mathrm{cmH_2O}$ for 6 hours to get moist condition. Mechanical breakdown simulates aggregate breakdown by mechanical force. Arai et al. (2003) and Le Bissonnais (1996) proposed the use of ethanol to exclude slaking by entrapped air,differential swelling and physico-

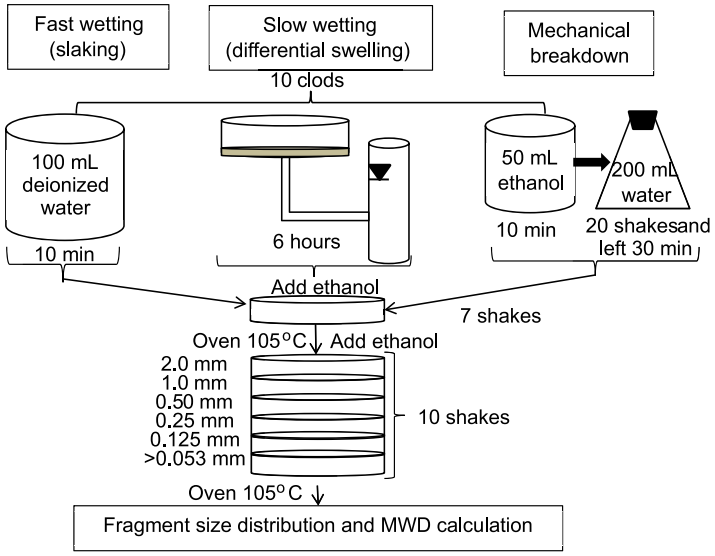


Fig. 1 Schematic diagram procedures for aggregate test with three treatments: fast wetting; slow wetting and mechanical breakdown.

chemical dispersion before the mechanical treatment. The ethanol reduces the thickness of diffuse double layers. Attraction forces between O-H bonds of ethanol and clay particles enable adjacent clay platelets to approach each other and reduce physico-chemical dispersion (Emerson, 1957) before the mechanical agitation. In the mechanical breakdown process, clods were submerged once in 50 mL ethanol (99.5 % v v^{-1}) for 10 min. The clods were then placed in 250 mL Erlenmeyer flasks containing 200 mL water. The flasks were shaken end over end for 20 times. The samples were then passed through a 0.053-mm mesh sieve to be separated into fragments < 0.053 mm and > 0.053 mm. Fragments < 0.053 mm were defined by the differences between their initial mass and the sum of the mass of the other six size fractions. Those > 0.053 mm were passed through six nested sieves: 2 mm, 1 mm, 0.500 mm, 0.25 mm, 0.125 mm, and 0.053 mm. They were sieved by the Yoder sieve (Yoder, 1936). After the three treatments: fast wetting, slow wetting and mechanical breakdown, aliquot of ethanol was added to the samples to prevent additional aggregate breakdown before wet sieving by Yoder sieve. Fragments remaining on the sieves were oven-dried at 105 °C for 24 h. Aggregate stability in each treatment was expressed using the size distribution of the three fragments: d $>$ 2mm; 2 mm$>$ d $>$ 0.25 mm; and d $<$ 0.25 mm. The mean weight diameter (MWD) was calculated from the mass fractions of the oven-dried samples (g) remaining on each sieve (after sieving) multiplied by the mean diameter (mm) of the adjacent mesh:

$$\mathrm{MWD} = \frac{\sum_{i=1}^{i=n} m_i \times d_i}{\sum m_i} \qquad (3)$$

where m_i is mass of aggregate fraction (i) of soil remaining on each sieve (after sieving) (g), and d_i is mean diameter of the adjacent mesh (mm).

Changes in MWD indicate that the clod size has decreased as a consequence of the breakdown caused by the three treatments.

2.5 Preparation for soil incubation

In the actual field, the soil must be plowed into smaller fragments to increase the contact surface area between the amendments and the soil particles. In the laboratory, this process was simulated by passing the soil blocks through a 2-mm mesh sieve before mixing them with the amendments. All samples were air-dried at room temperature to a constant mass before being mixed with the amendments. Twenty grams of air-dried soil (~ 4 % w w^{-1}) was used in each soil incubation.

2.6 Preparation and properties of amendments

Commercial chicken manure was obtained from the Tosho Company, Shizuoka Prefecture, Japan, and used as

Table 1 Properties of amendments.

Characteristics	Unit	Chicken manure	Chicken eggshell
Total carbon	%	38.7	16.4
Total nitrogen	%	3.6	1.9
C/N ratio		10.7	8.7
Organic carbon	%	38.1	4.7
pH		8.2	9.9
EC	dS m^{-1}	8.5	0.13
$CaCO_3$	%	5	97.8
Mass water content	%	13.3	1.7
P_2O_5	%	2.3	-
K^+	%	2.1	-
Zn^{2+}	mg kg^{-1}	200	-

Table 2 Treatments of soil incubation experiment. (LR: lime requirement).

Treatments	Explanation
(1) Control	No-amendment
(2) COM25	25 g chicken manure kg-soil^{-1}
(3) COM50	50 g chicken manure kg-soil^{-1}
(4) $CaCO_3 - 1/2$ LR	50 % LR chicken eggshell
(5) $CaCO_3 -$ LR	100 % LR chicken eggshell
(6) COM25 + $CaCO_3 - 1/2$ LR	25 g chicken manure kg-soil^{-1} + 50 % LR chicken eggshell
(7) COM50 + $CaCO_3 -$ LR	50 g chicken manure kg-soil^{-1} + 100 % LR chicken eggshell

compost. Chicken eggshell substituted for lime because it contained 97.8 % $CaCO_3$ (Table 1). Eggshells were collected from a canteen in the University of Tokyo. Chicken manure and eggshell were employed in this study because they are common wastes in the Mekong Delta region since poultry-raising is a popular farm management in the area. The properties of chicken manure and eggshell are summarized in Table 1. The EC and pH of the chicken manure were measured using a 1 : 5 solid/water suspension. The EC and pH of the eggshell were measured using a 1 : 100 solid/water suspension. The $CaCO_3$ content in the chicken manure and the eggshell was determined from an empirical standard curve (Loeppert et al., 1984). The organic carbon content in the chicken manure and the eggshell were determined using the following formula (Skjemstad and Baldock, 2006):

$$\text{Organic carbon}(\%) = \text{total carbon}(\%) - \left(\frac{\%CaCO_3 \times 12}{100}\right) \quad (4)$$

where $\%CaCO_3$ is known percentage of $CaCO_3$, 12 is molar mass of carbon in $CaCO_3$ (g mol^{-1}), 100 is molar mass of $CaCO_3$ (g mol^{-1}).

The compost was crushed and passed through a 1-mm mesh screen. It was applied at rates of 25 and 50 g kg-soil^{-1}. This can be converted to 25 t ha^{-1}and 50 t ha^{-1} with an assumption of incorporation into surface 10 cm thick soil layer and dry bulk density of 1 g cm^{-3}. Eggshells were rinsed with tap water and dried in an oven at 105 °C for 24 h. They were then crushed and passed through a 106-μm mesh screen. Eggshell-$CaCO_3$ application rates were based on the results of the lime requirement test (Sims, 1996). The amounts of $CaCO_3$ required to adjust the soil pH to 6.5 were set as the lime requirement (LR). Eggshell-$CaCO_3$ application rates of 50 % and 100 % of the lime requirement (1/2 LR and LR, respectively) were used.

2.7 Soil incubation

The incubation experiment consisted of seven treatments and three replicates as shown in Table 2. The incubation experiment was conducted for 45 days at a constant room temperature (25 °C). A 500 mL glass bottle with two three-way valves on its lid was used. This cap permitted gas exchange between the outside and inside of the bottle (Dumale et al., 2009). A gas sampling port with an internal septum was mounted on the lid to collect gas samples inside the bottles (Fig. 2). Before each bottle was sealed airtight, a 20-g soil sample mixed with amendments was added to it. Sufficient water was added to increase soil moisture to field capacity. Moist air was flushed head space of each bottle every two days. In this way, the air in the bottle could be replaced and replenished with outside air during the incubation periods. Failure to perform this procedure would result in a rapid increase in pressure of CO_2 (pCO_2) in the bottles and inhibition of microbial activity.

2.8 Gas sampling and gas analysis

Gas samples were drawn with a 10-mL plastic syringe (Nipro, Osaka, Japan) fitted with a 0.7 × 38.0 mm needle (Nipro, Osaka, Japan) to measure CO_2 emission.The gas samples were then transferred to a 5-mLvacuum glass vial fitted with a rubber septum. The CO_2 concentrations in 2-mL gas samples were measured by gas chromatograph (GC-2014, Shimadzu Corp., Kyoto, Japan).For homoge-

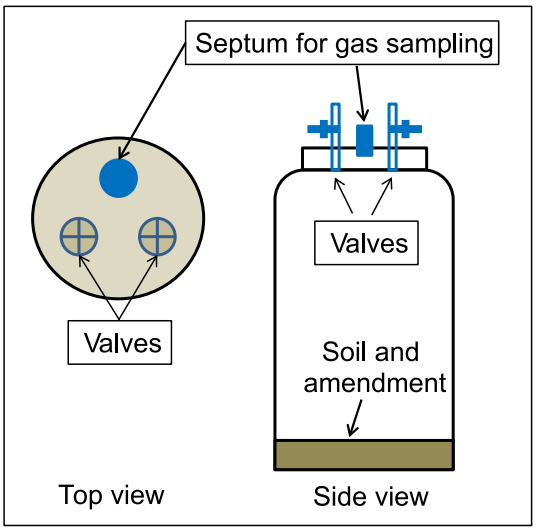


Fig. 2 Glass bottle used for soil incubation .

neous sampling, a syringe was connected to the three-way valve to mix the air inside the bottle 4–5 times before sampling. Gas samples were drawn at time zero (t_o) of incubation and at the sampling times (t_s) on days 1, 2, 3, 5, 7, 10, 20, 30, and 45 of incubation. The sampling time interval (t) is the difference between t_s and t_o. Since the moist air was flushed every 2 day, the gas samples at t_o were collected after flushing and those at t_s were collected before the next flush. The CO_2 emission rate was calculated using the following equation:

$$E = \frac{V \times (C_{ts} - C_{to}) \times M \times P \times 1000}{R \times T \times 100 \times w \times t} \quad (5)$$

where, E is gas emission rate (mg CO_2 g-soil^{-1} day^{-1}), V is volume of bottle (L), C_{ts} and C_{to} are concentration of CO_2 at t_s and t_o (vol.%), t is sampling time interval between t_s and t_o (day), M is molar mass of CO_2 (44 g mol^{-1}), P is air pressure (1 atm), R is gas constant (0.082 L atm K^{-1}mol^{-1}), T is temperature in Kevin (298K), and w is mass of air dry soil (g).

2.9 Aggregate stability measurement

The field must be plowed to break up the soil blocks into small fragments before adding the amendments. In this study, the soil blocks were sieved through a 2-mm mesh before being mixed with the amendments. During soil incubation, smaller fragments aggregated into larger, irregularly shaped blocks. For uniformity, all the soil samples after the halt of incubation were cut into 2–5 mm pieces. Based on the result of aggregate stability test, air-dried clods subjected to fast wetting process were employed to evaluate aggregate stability because they suffered the greatest aggregate deterioration. All samples were air-dried at room temperature to a constant weight. Aggregate stability was determined in the same way as for the fast wetting treatment (Le Bissonnais, 1996).

2.10 Statistical analysis

Means and standard deviations were reported for all measured parameters. Differences in treatment means were identified by one-way ANOVA at the 5 % significance level. Two-way ANOVA was used to determine the effects of the treatments and the moisture conditions on MWD. Differences between individual means were determined by the least significant difference (LSD) test at the 5 % significance level ($LSD_{0.05}$). A linear regression was applied to demonstrate linear correlations between soil pH and CO_2 emission.

3. Results

3.1 Soil properties

The properties of SS, AS, and ASS are shown in Table 3. The soils were clayey. ASS had the highest organic carbon content (5.7 %) followed by AS and SS (4.1 % and 2.4 %, respectively). Soil pH was lowest in ASS (2.7) and somewhat higher in AS and SS (4.6 and 5.5, respectively).

Table 3 Soil physico-chemical properties.

Soil types	Unit	Saline-sodic soil (SS)	Alluvial soil (AS)	Acid sulfate soil (ASS)
pH_{H_2O}		5.5	4.6	2.7
EC_e	dS m^{-1}	8.2	1.8	8.1
Organic carbon	%	2.4	4.1	5.7
Total nitrogen	%	0.12	0.24	0.23
C/N ratio		19.3	17.4	25.3
Sand	%	12.6	16.7	22.1
Silt	%	35.2	27.8	33.4
Clay	%	52.2	55.5	44.4
Soil texture		Clay	Clay	Clay
Bulk density	g cm^{-3}	1.1	1.1	0.6
Particle density	g cm^{-3}	2.8	2.6	2.5
Porosity	%	62.4	59.9	74.9
Moisture at field capacity	m^3 m^{-3}	0.49	0.41	0.24
K_{sat}	cm s^{-1}	4.4×10^{-7}	9.1×10^{-6}	1.7×10^{-2}
Soluble Na^+ (saturation extract)	mmol$_c$ L^{-1}	69.0	5.1	5.6
Soluble Ca^{2+}(saturation extract)	mmol$_c$ L^{-1}	5.1	12.0	6.6
Soluble Mg^{2+}(saturation extract)	mmol$_c$ L^{-1}	14.7	12.2	8.0
CEC	cmol$_c$ kg^{-1}	42.0	50.1	49.1
SAR_e	(mmol$_c$ L^{-1})$^{0.5}$	21.9	1.5	2.1
ESP_e	%	24.8	2.1	3.0
Lime requirement (LR)	g $CaCO_3$ kg-soil^{-1}	3.23	4.89	32.57

* subscript e denotes values for saturation extract

Table 4 Effects of initial moisture condition and breakdown processes on mean weight diameter (MWD) (mm) of three soil types: saline-sodic soil (SS), alluvial soil (AS) and acid sulfate soil (ASS). Initial aggregate size was 2–5 mm in diameter. Different lower case letters with a row show the significant difference in aggregate stability between initial conditions of soil moisture. Different upper case letters with a column show the significant difference in aggregate stability between breakdown processes at significance level of 5 % using LSD test. *P* value indicated the probability for the interaction effect of breakdown processes and initial moisture.

Breakdown process \ Initial moisture	Saline-sodic soil (SS)		Alluvial soil (AS)		Acid sulfate soil (ASS)	
	Dry	Moist	Dry	Moist	Dry	Moist
Fast wetting	1.91^{aA}	2.67^{bB}	2.37^{aA}	2.69^{bB}	2.36^{aA}	2.68^{bB}
Slow wetting	2.70^{aB}	2.68^{aB}	2.74^{bC}	2.70^{aB}	2.65^{aB}	2.71^{aB}
Mechanical breakdown	2.57^{aB}	2.55^{aA}	2.59^{aB}	2.50^{aA}	2.65^{bB}	2.58^{aA}
Breakdown process × initial moisture	$P = 9.31 \times 10^{-5}$		$P = 8.6 \times 10^{-7}$		$P = 0.00043$	

Table 5 Effects of initially dry clod sizes on fragment size distribution under the fast wetting process. "d" expressed fragment size. Different letters show the significant difference at significance level of 5 % using LSD test .

Soils	Initial clod sizes	Percentage of size fractions (%)		
		$d > 2$ mm	0.25 mm $< d <$ 2 mm	$d <$ 0.25 mm
Saline-sodic soil (SS)	1– 3 mm	21.61^{a}	58.24^{a}	20.15^{c}
	2– 5 mm	43.63^{b}	46.96^{a}	9.41^{b}
	5–10 mm	48.06^{b}	47.03^{a}	4.91^{a}
$LSD_{0.05}$		14.71	16.87	3.36
P		0.01	0.25	8.53×10^{-5}
Alluvial soil (AS)	1– 3 mm	48.48^{a}	41.79^{b}	11.14^{b}
	2– 5 mm	77.85^{b}	20.56^{a}	2.43^{a}
	5–10 mm	68.99^{b}	26.76^{a}	4.25^{a}
$LSD_{0.05}$		12.37	11.44	6.22
P		0.003	0.01	0.03
Acid sulfate soil (ASS)	1– 3 mm	74.61^{a}	15.38^{ab}	10.01^{b}
	2– 5 mm	79.70^{a}	16.92^{b}	4.04^{a}
	5–10 mm	87.50^{b}	9.70^{a}	2.80^{a}
$LSD_{0.05}$		7.69	6.51	2.79
P		0.04	0.08	0.002

Even the pH of SS was not optimum for plant growth, SS had high sodicity (ESP = 24.8 %) and high salinity (EC_e = 8.2 dS m^{-1}). ESP for ASS and AS was only 3.0 % and 2.1 %, respectively. EC_e was high for ASS and low for AS (8.1 dS m^{-1} and 1.8 dS m^{-1}, respectively). Since the pH of ASS was very low (2.7), it could have soluble Al (Tho and Egashira, 1976; Naramabuye and Haynes, 2006b; Khoi et al., 2010; Strawn et al., 2015) and soluble Fe (Stefansson, 2007; Strawn et al., 2015). In contrast, since the pH of AS was 4.6, it probably had relatively less soluble Al and Fe (Strawn et al., 2015). Other soil properties are summarized in Table 3.

3.2 Effects of initial soil moisture, breakdown processes and clod sizes on soil aggregate stability

3.2.1 Effects of initial soil moisture and breakdown processes on aggregate stability

The effects of initial soil moisture and breakdown processes on aggregate stability of 2–5 mm clods are shown in Table 4. The MWDs of the dry clods under fast wetting were lower than those under slow wetting and mechanical breakdown, and the differences were significant ($P <$ 0.01). Under fast wetting, the MWDs were lower for dry clods than moist clods, and the differences were significant ($P < 0.05$). Moist clods were less stable under mechanical breakdown than the slow and fast wetting treatments.

3.2.2 Effects of clod sizes on aggregate stability

Table 5 shows the fragment size distribution of dry clods after the fast wetting process for the three different initial sizes. After fast wetting, the portion of fragments > 2 mm

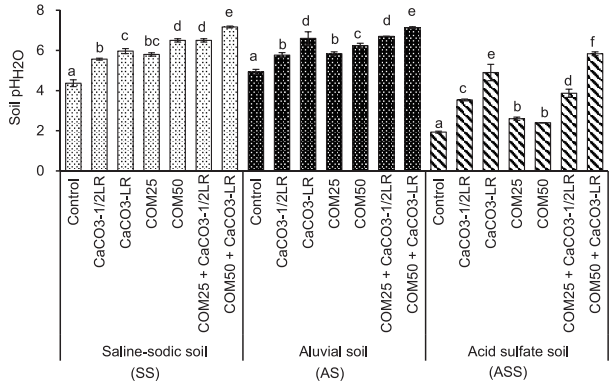


Fig. 3 Effects of compost and calcium carbonate application on pH of the soils after 45 days soil incubation. Vertical error bars show the standard deviation. Different letters show the significant differences between treatments at significance level of 5 % using LSD test: saline-sodic soil (SS) ($LSD_{0.05}$: 0.21; $P = 4.3 \times 10^{-12}$); alluvial soil (AS) ($LSD_{0.05} = 0.33$; $P = 2.2 \times 10^{-8}$) and acid sulfate soil (ASS) ($LSD_{0.05} = 0.39$; $P = 2.9 \times 10^{-11}$). "COM" and "LR" refer to Table 2 and Table 3, respectively.

was significantly ($P < 0.01$) greater for the 2–5 mm and the 5–10 mm clod group than for the 1–3 mm clod group. In contrast, the portion of fragments < 0.25 mm for the 1–3 mm size clods was twice of that of the two larger clod size groups. Dry clods of ASS showed that all three size groups had high portions of fragments > 2 mm. In ASS, the proportion of fragments > 2 mm increased with increasing initial clod sizes. The dry clods of 2–5 mm and 5–10 mm in size were more durable under fast wetting (Mekong Delta squall) than those 1–3 mm in diameter.

3.3 Effects of chicken manure-compost and eggshell-$CaCO_3$ application on soil improvement

3.3.1 Effects of compost and eggshell-$CaCO_3$ application on soil pH

Changes in soil pH after 45 days soil incubation with or without amendments are presented in Fig. 3. In this study, the initial soil pH was relatively low (2.7 in ASS, 4.6 in AS, and 5.5 in SS (Table 3)). After 45 days incubation, the pH of unamended ASS and SS decreased to 1.9 and 4.4, respectively whereas that of unamended AS rose slightly to 4.9. The pH of the amended soils was significantly higher ($P < 0.001$) than the unamended soils. When eggshell-$CaCO_3$ application increased from $1/2$ LR to LR, the soil pH increased from 5.6 to 6.0 in SS, from 5.8 to 6.6 in AS, and from 3.5 to 4.9 in ASS. By definition, the lime requirement (LR) is the amount of calcium carbonate required to raise the soil pH to be 6.5. However, the pH of ASS and SS after 45 days incubation was lower than this value.

Compost substantially increased soil pH from 5.8 to 6.5 in SS and from 5.8 to 6.2 in AS when the amount of compost increased from 25 g kg-soil^{-1} to 50 g kg-soil^{-1}. In ASS, the compost was less effective for increasing soil pH. Compost raised the pH of ASS to be 2.6 and 2.4 when it was applied at 25 and 50 g kg-soil^{-1}, respectively. The combination of $CaCO_3$ and compost increased soil pH more than either $CaCO_3$ or compost application. The combination raised soil pH to be 6.5, 6.7, and 3.9 in SS, AS, and ASS, respectively, at the rate of $1/2$ LR $CaCO_3$ and 25 g compost g-soil^{-1}. The combined application at rates of $CaCO_3$ (LR) and compost (50 g kg-soil^{-1}) could raise soil pH to be 7.2, 7.1, and 5.8 for SS, AS, and ASS, respectively.

3.3.2 Effects of compost and eggshell-$CaCO_3$ application on soil aggregate stability

MWD of the soils after 45 days incubation with or without amendments are shown in Table 6. The MWDs of the unamended soils and the soils amended with $CaCO_3$ alone were significantly ($P < 0.001$) smaller than those of the soils amended with either compost or compost combined with $CaCO_3$. In SS, aggregate breakdown after $CaCO_3$-LR application was greater than that observed after the application of $CaCO_3$-$1/2$ LR. In AS and ASS, there was no significant difference in MWDs between the two $CaCO_3$ doses. $CaCO_3$ application increased soil pH and thus could enhance clay dispersion by increasing negative charges on the clay particles (Roth and Pavan, 1991).

Compost application significantly ($P < 0.001$) increased MWDs for all the soils. Increasing compost from 25 g kg-soil^{-1} to 50 g kg-soil^{-1} significantly ($P < 0.001$) increased MWD from 2.32 mm to 2.53 mm and from 2.39 mm to 2.62 mm for SS and AS, respectively. The aggregate stability of ASS also increased significantly ($P < 0.001$) when compost was applied. Nevertheless, there was no significant difference in MWD for ASS between the two compost doses. The relatively higher MWDs of the three soils amended with combinations of compost and $CaCO_3$ indicated that the combined application of $CaCO_3$ and compost increased soil aggregate stability. Compost decomposition may have induced the production of microbial metabolites which enhanced aggregate stability (Carrizo et al., 2015).

3.3.3 Effects of compost and eggshell-$CaCO_3$ application on CO_2 emission

The total CO_2 emissions from the soils with or without the amendments after 45 days of incubation are shown in Fig. 4. Without the amendment, all the soils had low CO_2 emission levels (< 0.8 mg CO_2-C g-soil^{-1}). It was the initial soil pH rather than the soil organic carbon content responsible for the low CO_2 emission rates in the unamended soils. $CaCO_3$ application increased soil pH and, by extension, total CO_2-C evolution. $CaCO_3$ application significantly increased ($P < 0.001$) CO_2 emission for 45 days. In SS, the total CO_2 emission was 1.42 mg CO_2-C g-soil^{-1} at the lower $CaCO_3$ dose ($1/2$ LR) and 2.12 mg CO_2-C g-soil^{-1} at the higher $CaCO_3$ dose (LR). In AS, the total CO_2

emission was 2.01 mg CO_2-C g-soil^{-1} and 2.92 mg CO_2-C g-soil^{-1} at the $CaCO_3$ application rate of 1/2 LR and LR, respectively. The total CO_2 emitted in response to the $CaCO_3$ treatment was highest for ASS. This soil had total CO_2 emission of 7.47 mg CO_2-C g-soil^{-1} and 11.42 mg CO_2-C g-soil^{-1} at the 1/2 LR and LR doses, respectively.

Compost application enhanced total CO_2 emission during the 45 days incubation (Fig. 4). There was a significant difference ($P < 0.001$) in total CO_2 emission between compost-amended soils and unamended soils. The total CO_2 emission increased significantly ($P < 0.001$) with increase in compost application rate. In compost-amended SS, the total CO_2 emission was 6.87 and 12.76 mg CO_2-C g-soil^{-1} at the compost application rate of 25 and 50 g kg-soil^{-1}, respectively. In compost-amended AS, the total CO_2 emission was 7.66 and 14.66 mg CO_2-C g-soil^{-1} at the compost application rate of 25 and 50 g kg-soil^{-1}, respectively. However, the total CO_2 emission of compost-amended ASS was lower than those of the other soils. Compost application rates of 25 and 50 g kg-soil^{-1} resulted in CO_2 emission of 3.54 and 4.29 mg CO_2-C g-soil^{-1}, respectively. The extremely low pH of ASS could restrict microbiological activity and could account for low CO_2 emission.

Fig. 4 indicates that the soils amended with both eggshell-$CaCO_3$ and compost emitted more CO_2 than those treated with either $CaCO_3$ or compost alone. The total CO_2 emitted from SS amended with a combination of $CaCO_3$ (1/2 LR) and compost (25 g kg-soil^{-1}) was 7.99 mg CO_2-C g-soil^{-1}, which was higher than that for SS treated with either $CaCO_3$ or compost. The highest total CO_2 emission (14.11 mg CO_2-C g-soil^{-1}) was recorded for SS treated with the combination of $CaCO_3$ (LR) and compost (50 g kg-soil^{-1}). The total CO_2 emission for SS amended with $CaCO_3$ (LR) alone and compost (50 g kg-soil^{-1}) alone was 2.12 and 12.76 mg CO_2-C g-soil^{-1}, respectively. For AS, the total CO_2 emission was also the highest for the combination of $CaCO_3$ and compost. In ASS, the total CO_2 emission from the soil amended with $CaCO_3$ and compost combination was 10.94 and 16.84 mg CO_2-C g-soil^{-1} for the $CaCO_3$-1/2 LR and 25 g compost kg-soil^{-1}, and the $CaCO_3$-LR and 50 g compost kg-soil^{-1} treatments, respectively. The differences in CO_2 emission between the compost and $CaCO_3$ combination and the compost application alone were small for SS and AS. On the other hand, the differences in CO_2 emission between the compost and $CaCO_3$ combination and the compost alone were significantly large for ASS. The increase in soil pH (Fig. 3) by the combined application of compost and $CaCO_3$ could enhance soil CO_2 emission (Fig. 4).

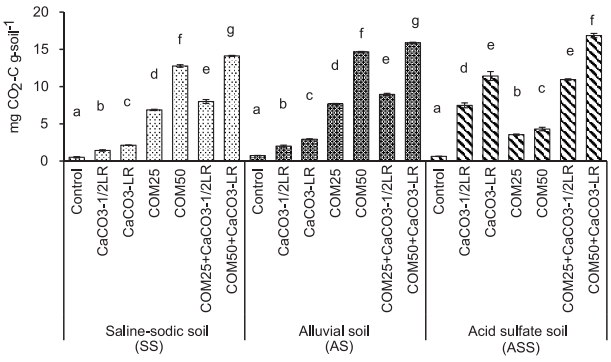


Fig. 4 Total CO_2 emission from compost and calcium carbonate application during 45 days soil incubation. Vertical error bars show standard deviation. Different letters show significant differences between treatments at the significance level of 5 % using LSD test: saline-sodic soil (SS) ($LSD_{0.05} = 0.24$; $P = 1.9 \times 10^{-22}$), alluvial soil (AS) ($LSD_{0.05} = 0.16$; $P = 1.6 \times 10^{-25}$) and acid sulfate soil (ASS) ($LSD_{0.05} = 0.52$; $P = 9.6 \times 10^{-18}$). "COM" and "LR" refer to Table 2 and Table 3, respectively.

Table 6 Effects of amounts of calcium carbonate and compost application on mean weight diameter (MWD) (mm) of soils after 45 days incubation. Aggregate analysis has been conducted on air dry soil having 2–5 mm in diameter. Aggregate analysis employed the fast wetting process. Different letters show significant differences between treatments at significance level of 5 % using LSD test. Mean ± standard deviation is shown in the same treatment of the same soil. "COM" and "LR" refer to Table 2 and Table 3, respectively.

Treatments	Saline-sodic soil (SS)	Alluvial soil (AS)	Acid sulfate soil (ASS)
Control	$0.57^{a} \pm 0.04$	$0.77^{a} \pm 0.08$	$1.22^{b} \pm 0.07$
$CaCO_3$-1/2 LR	0.94 ± 0.13	$0.93^{a} \pm 0.08$	$0.78^{a} \pm 0.10$
$CaCO_3$-LR	0.59 ± 0.08	$0.79^{a} \pm 0.06$	$1.08^{ab} \pm 0.28$
COM25	$2.32^{cd} \pm 0.10$	$2.39^{b} \pm 0.09$	$1.96^{c} \pm 0.09$
COM50	$2.53^{e} \pm 0.05$	$2.62^{c} \pm 0.02$	$1.99^{c} \pm 0.14$
COM25 + $CaCO_3$ − 1/2 LR	$2.25^{c} \pm 0.07$	$2.39^{b} \pm 0.14$	$2.22^{c} \pm 0.14$
COM50 + $CaCO_3$ − LR	$2.49^{de} \pm 0.04$	$2.51^{bc} \pm 0.08$	$2.20^{c} \pm 0.14$
$LSD_{0.05}$	0.169	0.183	0.324
P	1.04×10^{-13}	5.9×10^{-13}	2.8×10^{-7}

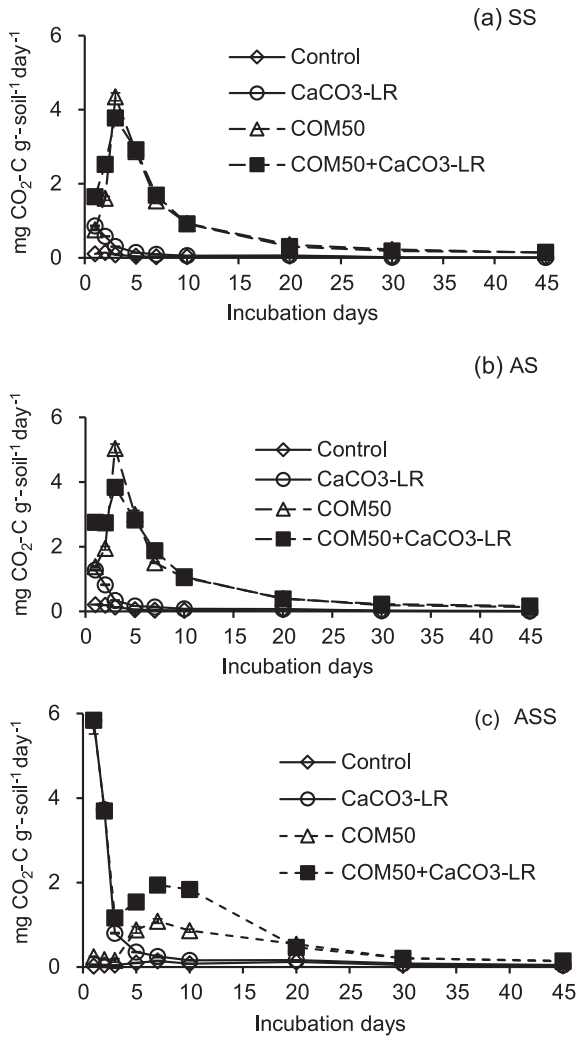


Fig. 5 Effect of calcium carbonate and compost on daily CO_2 emission rate during 45 days incubation: (a) saline-sodic soil (SS), (b) alluvial soil (AS) and (c) acid sulfate soil (ASS). Vertical error bars show standard deviation. "COM" and "LR" refer to Table 2 and Table 3, respectively.

Temporal changes in daily CO_2 emission rates during 45 days soil incubation are shown in Fig. 5. ASS with eggshell-$CaCO_3$ application showed the maximum CO_2 emission rate of 5.83 mg CO_2-C g-soil^{-1} day^{-1} at the first day after the application. For SS and AS, CO_2 emission also rose rapidly in the first day after $CaCO_3$ application (0.86 and 1.28 mg CO_2-C g-soil^{-1} day^{-1} for SS and AS, respectively) but its CO_2 emission rate was lower than that of ASS. The CO_2 emission rates abruptly ascended then descended for all three soils over the first 2 days after $CaCO_3$ application.

After compost application, the CO_2 emission rates rapidly increased for SS and AS over the first 5 days (Fig. 5). The highest CO_2 emission rate was observed at the 3rd day after compost application (4.35 and 5.04 mg CO_2-C g-soil^{-1} day^{-1} for SS and AS, respectively). Gradual declines in CO_2 emission rate occurred from the 5th day to the 20th day after amendment application. However, in ASS, low CO_2 emission rates were recorded for the first 3 days after compost application ($<$ 0.3 mg CO_2-C g-soil^{-1} day^{-1}). The CO_2 emission rate started to increase at the 5th day (0.88 mg CO_2-C g-soil^{-1} day^{-1}) and rose to 1.09 mg CO_2-C g-soil^{-1} day^{-1} by day 7. Thereafter, the CO_2 emission rates gradually declined until the 20th day.

The daily CO_2 emission rates of SS and AS amended with compost and $CaCO_3$ combination during 45 days soil incubation resembled to those obtained for SS and AS treated with compost alone (Fig. 5). The maximum CO_2 emission rate was recorded at 3rd day (3.78 and 3.84 mg CO_2-C g-soil^{-1} day^{-1} for SS and AS, respectively). For ASS, the daily CO_2 emission rate with the amendment combination was similar to those obtained with $CaCO_3$ alone within the first 2 days. The CO_2 emission rate then rose to be maximal, with 1.94 mg CO_2-C g-soil^{-1} day^{-1} by day 7. The rapid increase and decrease in daily CO_2 emission rate within the first 2 days may have been caused by $CaCO_3$ reactions. The subsequent increase in daily CO_2 emission rate between day 5 and day 20 could be explained by the microbial activity in compost disintegration.

4. Discussion

4.1 Effect of eggshell-$CaCO_3$ and compost application on soil pH

$CaCO_3$ is commonly used to alleviate low pH soils. After $CaCO_3$ application, pH of the soils was significantly improved (Fig. 3). The $CaCO_3$ application at the rate of lime requirement (LR) expected to raise the soil pH to be 6.5. However, the pH of SS and ASS remained $<$ 6.5 after 45 days incubation. While the pH of SS was raised to be 6.0 by the eggshell-$CaCO_3$ application at the rate of LR, the pH of ASS was raised to be 4.9. A possible explanation for low pH of ASS is gradual oxidation of pyrite, which was not considered when lime requirement test was conducted. In pyrite oxidation process, sulfuric acid (H_2SO_4) is produced and lowers pH of ASS (Attanandana and Vacharotayan, 1986). As Jayalath et al. (2016) suggested that pyrite oxidation process might continue over 70 days incubation. Besides, in lime requirement test, pH of the soil with $CaCO_3$ was evaluated after 24 hours incubation, and the pH of the soil with eggshell-$CaCO_3$ at the rate of LR was measured after 45 days incubation.

Application of compost could also raise soil pH. There were substantial rises in the pH of both SS and AS when the compost application rates increased from 25 g kg-soil^{-1} to 50 g kg-soil^{-1} (Fig. 3). On the other hand, the pH of ASS rose less in response to compost application. The addition of 50 g compost kg-soil^{-1} increased the pH of ASS from 1.9 as control treatment to 2.4. The $CaCO_3$

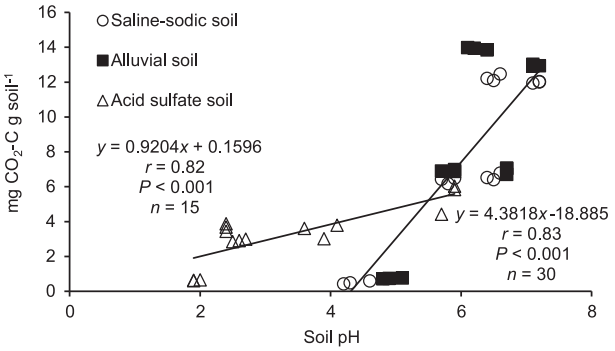


Fig. 6 Correlation between soil pH and CO_2 emission after application of compost with or without $CaCO_3$, where CO_2 emission from $CaCO_3$ was subtracted. The soil incubation was conducted at 25 °C, moisture at field capacity for 45 days.

in the chicken manure compost might contribute to raise soil pH. In this study, the chicken manure contained 5 % $CaCO_3$ (Table 1). The application of 25 and 50 g chicken manure kg-soil^{-1} equaled the 1.25 and 2.5 g $CaCO_3$ kg-soil^{-1} through chicken manure application. The eggshell-$CaCO_3$ application at the rate of $1/2$ LR and LR corresponded to 1.6 and 3.2 g $CaCO_3$ kg-soil^{-1}, respectively in SS and 2.45 and 4.9 g $CaCO_3$ kg-soil^{-1}, respectively in AS. The amount of $CaCO_3$ in the applied chicken manure at the rates of 25 and 50 g kg-soil^{-1} could help to rise pH of SS. Similar pH of AS was shown between the 25 g chicken manure kg-soil^{-1} and $1/2$ LR $CaCO_3$ although amount of $CaCO_3$ in the application rate of 25 g chicken manure kg-soil^{-1} was less a half than the amount of $CaCO_3$ at rate of $10/2$ LR. This suggested alternative process other than the reaction of $CaCO_3$ was responsible for rise in pH of AS. In ASS, the eggshell-$CaCO_3$ application at the $1/2$ LR and LR corresponded to 16.3 and 32.6 g $CaCO_3$ kg-soil^{-1}, respectively. The amount of $CaCO_3$ in applied chicken manure was minor and negligible. Therefore, $CaCO_3$ in chicken manure could contribute less on the rise in pH of ASS.

Aluminum-organic matter complexes are also expected to raise soil pH after compost addition (Naramabuye and Haynes, 2006a; Hue and Amien, 1989). Hydrolysis of soluble Al species may depress soil pH (Strawn et al., 2015), and Al-organic matter complexes depress soluble Al concentration. AS which had the initial pH of 4.6 may contain $Al(OH)^{2+}$ and Al^{3+} as Al species. Following to the application of organic matter, the rise in pH might be caused by Al-organic matter complexes (Naramabuye and Haynes, 2006a). In SS, since the initial pH was 5.5, it could contain an abundance of insoluble Al which may not complex with the organic matter. In contrast, ASS which had an original pH of 2.7 or less may have high concentrations of Al^{3+} (Khoi el al., 2010). Increase in the compost application did not increase the pH of ASS suggesting that Al-organic matter complexes could not affect the pH of ASS after compost application.

During compost decomposition by micro-organisms, hydron consumption by soluble organic anions in decarboxylation processes is expected to rise in soil pH (Yan et al., 1996; Naramabuye and Haynes, 2006b). Yan et al. (1996) used malate and citrate to discuss the role of biological decarboxylation of soluble organic anions on soil pH. They concluded that in aerobic conditions, neither denitrification nor reduction of Mn and Fe was responsible for soil pH rise. Naramabuye and Haynes (2006b) suggested that the decarboxylation of organic anions raised pH during manure decomposition. The biological decarboxylation of soluble organic anions may account for the rise in pH in addition to being a source of CO_2. In the decarboxylation process, hydron (H^+) is consumed by organic anions and releases CO_2 as the following equation:

$$R-CO-COO^- + H^+ \rightarrow R-CHO + CO_2 \qquad (6)$$

This process simultaneously raises soil pH and produces CO_2. Fig. 6 shows positive linear relationships ($r = 0.83$ for SS and AS, $r = 0.82$ for ASS) between soil pH and CO_2 emission for 45 days incubation with either compost or compost with eggshell-$CaCO_3$. In this figure, CO_2 emission was derived by subtracting CO_2 emission of the $CaCO_3$ applied soil from the total CO_2 emissions. It represents CO_2 emission from organic matter decomposition by microbiologies. Although quantitative discussion of pH and CO_2 production relationship requires soil buffering characteristic (Yan et al., 1996), the rise in both pH and CO_2 emission (Fig. 6) qualitatively suggested that the rise in soil pH following compost application was caused by decomposition of compost and subsequent decarboxylation (Yan et al., 1996). At least in the present study, both soil pH and CO_2 emission increased after adding either compost or compost with eggshell-$CaCO_3$ (Fig. 6).

4.2 Effect of eggshell-$CaCO_3$ and compost application on CO_2 emission

$CaCO_3$ application increased CO_2 emission rates. Rapid increase in CO_2 emission rates for all the soils occurred within the first 2 days after the $CaCO_3$ adding (Fig. 5). It could be a reaction between $CaCO_3$ and hydron in the soil solution. Dumale et al. (2011) reported a rapid increase in CO_2-C evolution within 2 days after $CaCO_3$ application in an Ultisol. They suggested that the $CaCO_3$ was promptly solubilized in low-pH soils like Ultisols. In this study, the maximum CO_2 emission rate was found at first day after $CaCO_3$ amendment followed by an abrupt decline thereafter. For the soils amended with $CaCO_3$, the CO_2 emission rates were high in ASS and low in both SS and AS. The differences in the initial soil pH may account for the

differences in CO_2 emission rates among the soils following $CaCO_3$ application. In the present study, ASS had the lowest pH (Table 3). Much hydron in ASS reacted with the applied $CaCO_3$, and released CO_2 much faster than SS and AS whose pH was comparatively higher.

Changes in CO_2 emission rates suggested that the soils with compost had higher microbiological activity, and thus, higher CO_2 emission rates. However, the CO_2 emission rates in response to compost application varied among soil types. A substantial increase in CO_2 emission rate occurred within the first 5 days in compost-amended SS and AS (Fig. 5a and 5b). In ASS, a gradual rise in CO_2 emission rate began on day 5 and continued until day 20 (Fig. 5c). The changes in CO_2 emission in the latter stage of incubation after compost application relied to the activity of micro-organisms. The extremely low pH of ASS could inhibit microbiological activity. A suitable pH range for microbial growth is 5-7 (Pietri and Brookes, 2008). AS and SS with compost application had relatively higher initial pH and showed quick increase in CO_2 emission rate in the early stage of incubation (Fig. 5a and 5b). In contrast, extremely acidic ASS could have limited microbial activity and gradually increased CO_2 emission rates in the latter stage of soil incubation with compost application (Fig. 5c).

There were similar trends of CO_2 emission rates of SS and AS in response to compost application and combination of compost and $CaCO_3$ application (Fig. 5a and 5b). For both AS and SS, the CO_2 emission rates increased within the first 5 days after application of either compost or combination of compost and $CaCO_3$. In case of the $CaCO_3$ application alone, there was a small increase in CO_2 emission rate induced by $CaCO_3$ reactions within the first 2 days. Therefore, CO_2 emission rate of AS and SS proceeded more than 2 days after the combined application of compost and $CaCO_3$ could be responsible for an increase in microbial decomposition activity (Fig. 5a and 5b). In strongly acidic ASS, there were similar temporal changes in CO_2 emission rate within the first 2 days after $CaCO_3$ application and the combined application of compost and $CaCO_3$. The second increase in CO_2 emission rate between day 5 and day 20 in response to the application of the combination of compost and $CaCO_3$ was twice of that for the compost alone (Fig. 5c). This second rise in CO_2 emission rate could be the result of the enhancement of microbial activity. It implied that the rise in pH induced by $CaCO_3$ in combination with compost could produce more CO_2 by microbiological activity in compost decomposition in the latter stage of incubation. It showed that the combined application of eggshell-$CaCO_3$ and compost could increase soil CO_2 emission rate more than either eggshell-$CaCO_3$ or compost alone. The rise in soil pH caused by the application of compost and $CaCO_3$ (Fig. 3) could enhance soil CO_2 production (Fig. 4). Condron et al. (1993) reported that soil CO_2 respiration in acid soils (pH 4.43) with addition of lime and litter was much more than that with addition of either lime or litter for 17 weeks of incubation. However, Condron et al. (1993) showed weekly CO_2 emission which was from the first week to the 17^{th} week. As Dumale et al. (2011) suggested that CO_2 emission following lime application occurred within a few days. Thus, weekly CO_2 emission rate cannot separate sources of CO_2, i.e. $CaCO_3$ and organic matter. In the present study, the rapid increase in daily CO_2 emission rate occurred within the first two days. It was due to eggshell-$CaCO_3$ reaction. CO_2 emission proceeded more than 2 days and later was from chicken manure compost decomposition by microbiological activity. Xue et al. (2010) reported an increase in soil microbiological population following the addition of $CaCO_3$ to acidic tea orchard soils. Pietri and Brookes (2008) stated that soil CO_2 evolution from microbiological activity increased with pH. The relatively higher CO_2 evolution rates from the combined application of $CaCO_3$ and compost suggested that $CaCO_3$ in the combination could be highly effective at promoting microbiological activity in very acidic soils.

4.3 Effect of eggshell-$CaCO_3$ and compost application on aggregate stability

Tillage is conducted to prepare the seedbed to support seedling germination and plant growth. Aggregate stability is influenced by the clod size produced by tillage. Under fast wetting condition, dry clods 2–5 mm and 5–10 mm in size were more durable than those 1–3 mm in diameter (Table 5). Dry clods subjecting to fast wetting process were less stable in the three soils. In tropical areas like Mekong Delta region, dry soils are exposed to prolonged sunny days. Furrow irrigation, border irrigation or heavy rainfall may cause fast wetting. In the present study, this scenario was simulated by dry clods subjecting to fast wetting process. Fast wetting of air-dried 2–5 mm clods was employed to assess aggregate stability after incubation of the soils with the amendments.

The smaller MWDs of the unamended soils and those amended with eggshell-$CaCO_3$ showed aggregate deterioration. According to Roth and Pavan (1991), liming increased soil pH and enhanced clay dispersion by increasing negative charges of clay particles. The amounts of applied $CaCO_3$ used in this study did not significantly affect MWD. Higher MWDs were observed in soils added with compost and combinations of compost and eggshell-$CaCO_3$. The aggregate stability of AS and SS was statistically greater at the higher amendment dose than the lower dose. The aggregate stability of ASS significantly increased with the addition of compost. Nevertheless, there was no significant difference in MWD of ASS between the

two compost doses. The increase in MWD in response to compost amendment implied that compost played an important role in stabilizing soil aggregates. Organic amendments may help stabilize aggregates by inducing microbiological decomposition of organic matter (Griffiths and Jones, 1965). Organic products from the microbiological decomposition of organic residues may act as binding agents and enhance aggregate stability by resisting the effects of slaking under fast wetting (Carrizo et al., 2015). Earlier studies have discussed the roles of organic binding agents, clay-polyvalent cations-organic matter, and clay-organic matter in stabilizing aggregates against slaking and clay dispersion in soils (Tisdall and Oades, 1982; Nelson and Oades, 1998). In this study, chicken manure was used as a compost. It is an easily decomposable organic carbon source with a low C/N ratio (Table 1). The organic compounds released by decomposing process may bind soil particles and enhance aggregation. The amendment consisting of compost and $CaCO_3$ was highly effective at increasing pH and stabilizing the aggregates of the three soils.

5. Conclusions

In the results of the aggregate stability test, mean weight diameter (MWDs) was the lowest for dry clods subjected to fast wetting. MWDs also suggested that saline sodic soil (SS) had the most fragile aggregates, followed by alluvial soil (AS) and acid sulfate soil (ASS). In the actual field, surface soils become dry when they are exposed to prolonged sunny days. Substantially lower MWD suggests heavy rainfall events or abrupt irrigation on dry soil surfaces may degrade aggregates.

In the Mekong Delta region, there is a great deal of interest in soil pH amelioration. $CaCO_3$ is commonly used to raise soil pH. The pH of SS and AS was improved by adding either $CaCO_3$ or compost or both. The only exception was for compost-amended ASS, where compost application could not raise pH. Only eggshell-$CaCO_3$ or eggshell-$CaCO_3$ with compost was effective to raise pH of ASS. Improving soil pH as well as aggregate stability is desirable to intensify soil productivity. The present study showed that although the physicochemical properties of the three soils differed, their aggregates deteriorated with eggshell-$CaCO_3$ application while soils amended with either chicken manure compost or chicken manure compost with eggshell-$CaCO_3$ presented greater aggregate stability. Relationships between soil pH and CO_2 emission from compost applied soils suggested that microbiological activity was affected by soil pH. Upon compost application to the three soils, CO_2 emission was more in SS and AS that had slightly low pH than ASS that had extremely low pH. In slightly acidic soils like SS and AS, the highest CO_2 emission rates were measured within the first 5 days after compost application, while ASS took more time to show peak CO_2 emission rate. The combination of compost and $CaCO_3$ increased soil pH and CO_2 emission in all three soils. This suggested that microbiological activity was enhanced by an increase in soil pH by $CaCO_3$ in combination of chicken manure compost and eggshell-$CaCO_3$. The rise in soil pH induced by the $CaCO_3$ in the compost and eggshell-$CaCO_3$ combination could create a suitable environment for microorganism growth and promote compost decomposition. The organic by-products of microbial compost decomposition may enhance aggregate stability. The results of this study indicated that the combination of eggshell-$CaCO_3$ and chicken manure compost that are common agricultural wastes in Mekong delta region improved soil pH and sustain aggregate stability. This information may help farmers to improve quality of low pH soils.

Acknowledgments

This study was partly supported by Kakenhi (15H02467). The author would like to express sincerely thanks Japanese Government who supported MEXT scholarship for PhD research. Many sincerely thanks would like to send Mr. Hiromi Imoto because of his enthusiastic helps to fulfill experiments. The authors thank to all members of the Laboratory of Soil Physics and Soil Hydrology, Department of Biological and Environmental Engineering of the University of Tokyo for their assistance in soil sampling.

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要　　旨

メコンデルタには硫酸酸性土壌や塩類土壌が広く分布する．土壌の化学性の改良の際には，物理性の劣化を最小限にすることも重要である．また，メコンデルタの土壌団粒については，よくわかっていない．そこで本研究では, 塩性 Na 土（SS，pH＝ 5.5），硫酸酸性土 (ASS，pH＝ 2.7) と沖積土（AS，pH＝ 4.6) に卵殻（$CaCO_3$ の代替）ならびに鶏ふん堆肥（以下鶏ふん）を施用した後，土壌 pH と団粒安定性の変化を調べた．培養は，土壌と鶏ふん，卵殻を混合した後，室温 25 °C の下，圃場容水量で適宜換気，CO_2 測定をしながら 45 日間実施した．団粒安定性評価は予め行った団粒安定性試験を参考に培養後の土壌から 2 ～ 5 mm サイズの風乾試料を調製し，これを急速に漬水した後の平均重量直径で行った．CO_2 発生量から，鶏ふん施用 SS，AS では，鶏ふんの分解が示唆されたが，ASS ではほとんど分解しなかった．鶏ふん · 卵殻混合物施用の場合，ASS では，初期に卵殻の炭酸 Ca の反応，その後は鶏ふん等有機物の分解が，SS と AS ではいずれも鶏ふん等有機物の分解が CO_2 発生の主因であると考えられた．鶏ふんは，施用量に応じて SS と AS の pH を改善したが ASS では pH 改善効果がなかった．鶏ふん · 卵殻混合物を施用すると ASS において卵殻のみの場合よりも有意に pH が上昇し，有機物の分解も pH 改善に寄与していることが示唆された．鶏ふんならびに鶏ふん · 卵殻混合物の施用後，団粒安定性が向上した．特に pH が非常に低い ASS において，卵殻の炭酸 Ca による pH 上昇が鶏ふん等有機物分解による，団粒安定性向上促進に寄与したと考えられる．

キーワード：土壌改良，土壌構造，鶏ふん堆肥，卵殻，土壌劣化