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REVIEW

# Soybean Yield Response to Liming Materials in Paddy-Upland Rotation Fields

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## Abstract

This review summarizes the findings of previous research by Takamoto et al. on the effects of liming materials on soybean growth and yield in paddy-upland rotation fields in Japan. A wide survey, encompassing 456 fields in 16 prefectures, revealed that excessive exchangeable magnesium (Mg) was associated with lower yields. Further pot and field experiments using liming materials showed that, in fields with excessive exchangeable Mg, increased exchangeable calcium (Ca) significantly enhanced soybean yield, but this positive effect was offset when exchangeable Mg also increased. Comparative analysis of the effects of calcium carbonate ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] demonstrated that both materials significantly increased soil pH, exchangeable Ca content, and soybean yield compared with the control (no lime). However, $CaCO_3$ improved soybean yield more than dolomite did by enhancing soybean shoot growth. These findings highlight the importance of managing both soil pH and exchangeable cation contents for soybean production in paddy-upland rotation fields. Further research is needed to clarify the mechanisms underlying these dynamics and optimize liming strategies under varying soil conditions.

**Discipline:** Agricultural Environment
**Additional key words:** soybean, paddy-upland rotation field, liming, exchangeable cations, soil pH

## Introduction

Soybean demand in Japan has remained high since 2013, with most of the supply still reliant on imports (MAFF 2025). Domestically produced soybeans are primarily used for food, and the soybean self-sufficiency rate is estimated to be only 20%-25% (MAFF 2025). Although there is a growing need to increase domestic production, yields have declined since 2000 (MAFF 2025, SBJ 2025). A major factor contributing to low yields is waterlogging damage caused by poor drainage in paddy-upland rotation fields (Kokubun 2013), which account for 80% of Japan's soybean production area (SBJ 2025). In recent years, some studies have also identified drought stress as a potential yield-limiting factor in these fields (Konno et al. 2020, Kumagai et al. 2018). Therefore, numerous studies in Japan have focused on clarifying soil moisture dynamics in paddy-upland rotation fields to develop measures to improve soybean yields (Kaneta et al. 2004, Matsuo et al. 2013, Takahashi et al. 2006, Takahashi et al. 2018).

In contrast to soil physical properties, soil chemical properties yield inconsistent conclusions because soybean response to fertilization is limited. Although some studies have proposed available soil nitrogen (Av-N) as a potential yield-limiting factor (Nira & Hamaguchi 2012, Nira et al. 2020), its relationship with soybean yield remains unclear (Kawarada et al. 2022, Kuno et al. 2021). Indeed, it has been shown that improving Av-N levels via compost application has a negligible effect on soybean yield (Hirokawa et al. 2011, Nira & Hamaguchi 2012, Nira et al. 2020, Sumida et al. 2005, Takamoto et al. 2025). Soil pH has also been proposed as a chemical property associated with yield improvement, but relevant studies exploring this hypothesis in Japan are limited (Takamoto et al. 2021, Takamoto et al. 2023a, Tsubouchi

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& Saito 2010).

The object of this review is to provide an overview of why lime applications increase soybean yield, focusing not only on soil pH but also on base cations such as calcium and magnesium. To address this knowledge gap, Takamoto et al. (2020) first examined the relationship between soybean yield and soil chemical properties in paddy-upland rotation fields using data collected from a wide-area survey in Japan.

## Relationships between soil chemical properties and soybean yield

Previous wide-area surveys in Japan have examined the relationship between soybean yield and soil properties at the prefectural and regional scales. However, varying results were obtained (Hattori et al. 2013, Ishitsuka et al. 2016, Odahara et al. 2012, Takahashi et al. 2005, Takahashi et al. 2014, Yamane & Kokubun 2014), suggesting that the yield-limiting properties of soils differ by location. To identify common yield-limiting properties across soybean production sites in Japan, Takamoto et al. (2020) analyzed topsoil samples collected over a wide area covering 456 paddy-upland rotation fields at 228 sites in 16 prefectures. Two fields were surveyed at each site and categorized as high or low yield based on soybean yield. The average yields of the high- and low-yield groups were 3.1 t $ha^{-1}$ and 2.5 t $ha^{-1}$, respectively (Table 1). The Wilcoxon signed-rank test was used to compare the chemical properties of topsoil samples between the two groups. Three properties were identified as significant: exchangeable magnesium (Mg), the ratio of Mg to potassium (Mg/K), and the ratio of calcium to Mg (Ca/Mg) (Table 1). Exchangeable Mg and Mg/K were higher in the low-yield group, whereas Ca/Mg was higher in the high-yield group (Table 1). These findings suggested that excessive exchangeable Mg may limit soybean yield in paddy-upland rotation fields. Considering that the concentrations of exchangeable cations, including Ca and Mg, are modified by liming materials, Takamoto et al. (2021) examined whether the application of such materials could improve soybean yield in paddy-upland rotation fields with excessive exchangeable Mg.

## Soybean growth response to Ca supplied through liming materials in soils with excessive exchangeable Mg

Liming materials generally alter both soil pH and exchangeable cation contents, but how these factors separately affect soybean growth and yield has not been sufficiently investigated (Komatsu & Iwasa 1989). To clarify these effects, Takamoto et al. (2021) conducted a pot experiment and a field experiment using lime. The experiments were conducted on soils from paddy-upland rotation fields in which exchangeable Mg exceeded 2,000 mg MgO $kg^{-1}$ (Tables 2, 3). The pot experiment showed that improving exchangeable Ca alone using calcium sulfate ($CaSO_4$) had no effect on soybean yield. In contrast, improving both exchangeable Ca and soil pH by applying $CaSO_4$ in combination with calcium hydroxide significantly increased soybean yield (Fig. 1). In contrast, the field experiment showed that the application of phosphogypsum (1,111 $gm^{-2}$) increased soybean yield (Fig. 2). Minimal variation in soil pH was

**Table 1. Comparison of the chemical properties of topsoil samples between high- and low-yield groups at 228 sites in Japan using the Wilcoxon signed-rank test by Takamoto et al. (2020)**

| Variable | Unit | High yield (median[mean]) | Low yield (median [mean]) | *p*-value by Wilcoxon test |
|---|---|---|---|---|
| Yield | t $h^{-1}$ | 3.17 [3.14] | 2.51 [2.50] | < 0.001*** |
| Total N | % | 0.190 [0.224] | 0.181 [0.221] | $0.172^{ns}$ |
| Soil pH | - | 5.80 [5.84] | 5.84 [5.85] | $0.230^{ns}$ |
| Av-$P_2O_5$ | mg $kg^{-1}$ | 181 [218] | 167 [217] | $0.182^{ns}$ |
| Ex. $K_2O$ | mg $kg^{-1}$ | 280 [331] | 279 [329] | $0.644^{ns}$ |
| Ex. CaO | mg $kg^{-1}$ | 2305 [2549] | 2368 [2552] | $0.825^{ns}$ |
| Ex. MgO | mg $kg^{-1}$ | 353 [442] | 412 [476] | 0.040* |
| Ca/K | - | 13.7 [16.8] | 13.9 [16.4] | $0.927^{ns}$ |
| Ca/Mg | - | 4.41 [4.98] | 3.99 [4.64] | 0.007** |
| Mg/K | - | 3.24 [4.03] | 3.44 [4.29] | 0.027* |

ns, not significant; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$
Av, available; Ex., exchangeable
The hyphen indicates a dimensionless quantity.

observed between post-harvest soil samples collected from plots with and without phosphogypsum. In contrast, exchangeable Ca content differed significantly (Table 3). Phosphogypsum application also increased available phosphorus (P) content (Table 3). These findings suggest that in fields with excessive exchangeable Mg, increasing exchangeable Ca alone is unlikely to be sufficient for enhancing soybean yield, and the yield response likely

**Table 2. Soil pH and exchangeable calcium (CaO) and magnesium (MgO) contents after the pot experiment by Takamoto et al. (2021)**

| Treatment | Soil pH | Exchangeable CaO (mg $kg^{-1}$) | Exchangeable MgO (mg $kg^{-1}$) | Yield (g $pot^{-1}$) |
|---|---|---|---|---|
| | | ---------- 2018-2019 ---------- | | |
| Control | 5.23 | 4494 | 2498 | 45.4 |
| Ca amendment | 5.00 | 5765 | 1585 | 45.4 |
| Ca+pH amendment | 5.67 | 6209 | 1851 | 54.4 |
| | | ---------- 2019 ---------- | | |
| Control | 5.32 | 4465 | 2350 | 44.9 |
| $CaCO_3$ | 5.92 | 5836 | 2325 | 63.2 |
| Dolomite | 6.36 | 4973 | 2845 | 44.2 |

Dolomite refers to $CaMg(CO_3)_2$.
Ca amendment indicates the application of calcium sulfate dihydrate ($CaSO_4$), and Ca+pH amendment indicates the combined application of $CaSO_4$ and calcium hydroxide [$Ca(OH)_2$].

**Table 3. Soil pH, exchangeable calcium (CaO) and magnesium (MgO) contents, and available P content after the field experiment by Takamoto et al. (2021)**

| Treatment | Soil pH | Exchangeable CaO (mg $kg^{-1}$) | Exchangeable MgO (mg $kg^{-1}$) | Available P (mg $kg^{-1}$) | Yield (g $m^{-2}$) |
|---|---|---|---|---|---|
| | | ---------- 2018-2019 ---------- | | | |
| Control | 5.01 | 4102 | 2577 | 95.7 | 149 |
| Gypsum | 4.75 | 5872 | 2236 | 135.2 | 202 |

Gypsum refers to phosphogypsum.

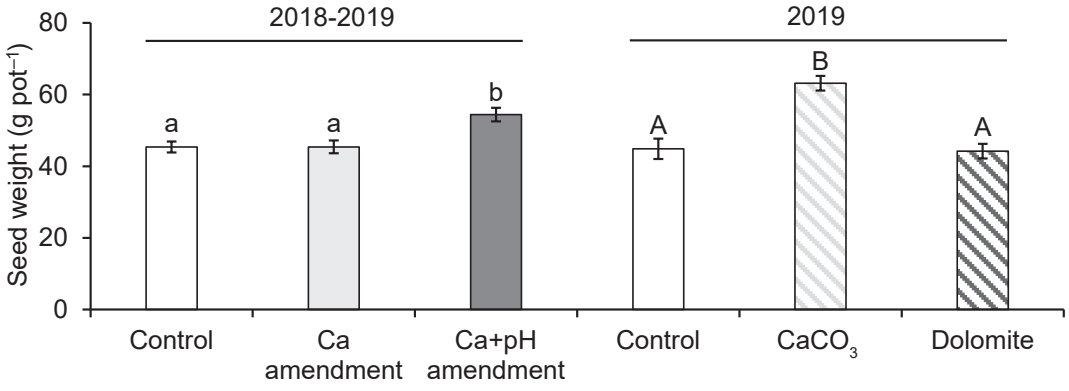



**Fig. 1. Weight of soybean seeds under different treatments in the pot experiment by Takamoto et al. (2021)**
Error bars represent standard errors. Different letters indicate significant differences among treatments according to Tukey's test at the 5% level, with uppercase and lowercase letters representing separate comparison groups. *Note: Dolomite refers to $CaMg(CO_3)_2$. Ca amendment indicates the application of calcium sulfate dihydrate ($CaSO_4$), and Ca+pH amendment indicates the combined application of $CaSO_4$ and calcium hydroxide [$Ca(OH)_2$].*

depends on changes in Ca combined with soil pH and/or additional nutrients such as P. In the one-year pot trial, the application of calcium carbonate ($CaCO_3$) increased yield, whereas adding dolomite had no effect (Fig. 1). Thus, the pot experiment by Takamoto et al. (2021) consistently showed the positive effect of improving both exchangeable Ca and soil pH on soybean yield, whereas simultaneously increasing exchangeable Mg may offset the effect. To further elucidate this offsetting dynamic, Takamoto et al. (2023a) comparatively analyzed the effects of $CaCO_3$ and dolomite on soybean growth and yield in paddy-upland rotation fields.

## Different response patterns of soybean yield to calcium carbonate and dolomite

Both $CaCO_3$ and dolomite increase soil pH and contain carbonate as the anion, but the former supplies only Ca, whereas the latter supplies both Ca and Mg. To generalize comparisons of the effects of these liming materials, such comparisons should be conducted in fields with exchangeable Mg at the national means (Table 1), rather than in fields with excessive exchangeable Mg (Tables 2, 3). Takamoto et al. (2023a) separately examined the effects of $CaCO_3$ and dolomite on soybean yield over a two-year period in a paddy-upland rotation field in Daisen City, Akita Prefecture. They revealed that soil pH increased to a similar extent after the application of both liming materials. Exchangeable Ca content also increased under both treatments, whereas exchangeable Mg content increased only with the addition of dolomite (Table 4). Treatment with $CaCO_3$ significantly increased soybean shoot growth at the flowering (R1) stage and beginning of seed growth (R5) compared with the control (no lime), whereas the application of dolomite did not have such effect (Fig. 3). Thus, the addition of $CaCO_3$ resulted in a higher yield compared with the control and the addition of dolomite (Fig. 3). Although dolomite did not increase soybean growth, it increased soybean yield relative to the control (Fig. 3) by suppressing soil-borne diseases (Takamoto et al. 2023a). This result with dolomite contradicts the pot experiment (Fig. 1) by Takamoto et al. (2021), and the discrepancy may be attributable to the presence or absence of soil-borne diseases. In that pot experiment, no clear signs of soil-borne diseases were detected (data not shown). This comparative experiment is still ongoing. On average, across the five soybean crops, both $CaCO_3$ and dolomite significantly increased yield compared with the control (data not shown). However, when analyzing each crop individually, dolomite showed no statistically significant increase in yield in any of the five trials (data not shown). These results suggest that under conditions where soil pH is sufficiently improved, concomitant increases in exchangeable Mg may offset the positive effect of exchangeable Ca on soybean yield. The mechanism underlying the consistent effect of $CaCO_3$ on yield remains under investigation, and current findings indicate that maintaining stable soybean growth until the flowering stage may be critical.

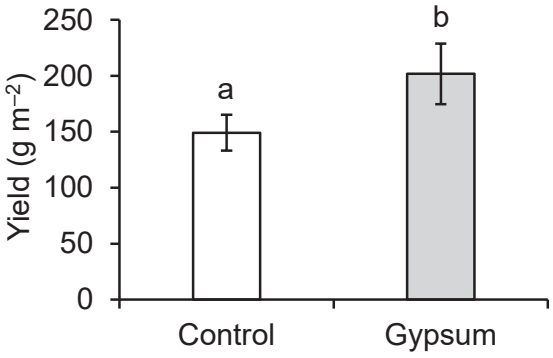



**Fig. 2. Soybean yield under different treatments in the field experiment conducted by Takamoto et al. (2021)**
Error bars represent standard errors. Different letters indicate significant differences among treatments, as determined by Tukey's test at the 5% level. *Note: Gypsum refers to phosphogypsum.*

**Table 4. Soil pH and exchangeable calcium (CaO) and magnesium (MgO) contents after the field experiment by Takamoto et al. (2023)**

| Treatment | Soil pH | Exchangeable CaO (mg $kg^{-1}$) | Exchangeable MgO (mg $kg^{-1}$) | Yield (g $m^{-2}$) |
|---|---|---|---|---|
| | | 2019-2020 | | |
| Control | 5.64 | 3325 | 380 | 246 |
| $CaCO_3$ | 6.19 | 4872 | 379 | 348 |
| Dolomite | 6.08 | 4011 | 665 | 304 |

Dolomite refers to $CaMg(CO_3)_2$.

## One consideration of the mechanism underlying soybean yield increases resulting from liming

The results obtained from comparative experiments by Takamoto et al. (2023a) demonstrated that $CaCO_3$ application produced a higher yield than dolomite application. Although this finding was consistent with pot tests by Takamoto et al. (2021), it contradicts the findings of Pagani & Mallarino (2012) and Vetsch & Randall (2004). This discrepancy may be explained by improved soybean growth up to the R1 stage by $CaCO_3$ (Fig. 4). Tamura et al. (1993) demonstrated that in the Tohoku region, soybean growth before flowering is critical for high soybean yields. All studies by this author, including Takamoto et al. (2023a), were conducted in the Tohoku region, specifically in Akita Prefecture. Additionally, vegetative growth up to flowering can be enhanced through fertilization (Takamoto et al. 2025). Thus, the growth gain may contribute to the greater yield observed with $CaCO_3$ compared to dolomite (Fig. 4). However, the mechanism underlying this improvement with $CaCO_3$ remains unclear at present. These findings suggest that lime fertilization is effective in regions such as Tohoku, where vegetative growth primarily determines soybean yield.

## Practical considerations for liming in soybean fields under paddy-upland rotation

The studies by Takamoto et al. cited in this review indicate that applying liming materials to adjust exchangeable cation content is important for soybean production in paddy-upland rotation fields. However, the robustness of this approach requires careful evaluation, as some studies have reported that exchangeable cations have no significant effects on crop growth and yield (Chaganti & Culman 2017, Culman et al. 2021, Gaspar & Laboski 2016, Leiva Soto et al. 2023). Changes in exchangeable cation content influence elemental concentrations in plants, and thus liming materials may alleviate nutrient deficiencies and toxicities. Other studies have also reported reduced growth and yield without visible symptoms, a phenomenon known as "hidden hunger" (Ortel et al. 2022, Ortel et al. 2023). To detect such conditions, elemental analysis of plant tissues is required, and to effectively adjust exchangeable base contents using liming materials, it is essential to determine sufficiency ranges for various elemental concentrations in both the soil and soybean plant tissues.

In paddy-upland rotation fields, soil acidification has recently become widespread. Takamoto et al. (2023b) reported that 85% and 20% of 192 fields in eastern Japan had soil pH levels ≤ 6.0 and ≤ 5.0, respectively. Soil acidification generally limits crop production, and soybean yield has been shown to decline at soil pH ≤ 6.0 (Slaton et al. 2013). Biological fixation of atmospheric $N_2$ by leguminous crops also acidifies the soil because excess cation uptake, especially $K^+$, requires charge balance via net proton release (Bolan & Hedley 2003, Goulding 2016, Neumann & Römheld 2012). Moreover, exchangeable cations leach from paddy-upland rotation fields during the flood season (Wakayama & Kawamoto

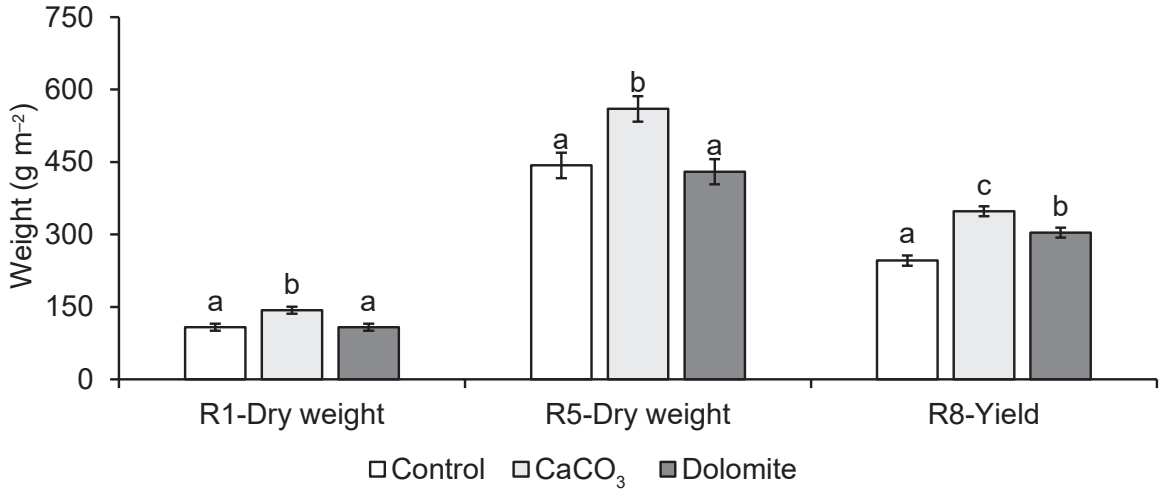



**Fig. 3. Shoot dry weight of soybean plants at stages R1 and R5 and soybean yield (R8) under different treatments in the field experiment by Takamoto et al. (2023)**
Error bars represent standard errors. Different letters within each growth stage indicate significant differences among treatments, as determined by Tukey's test at the 5% level.

1983). Therefore, liming is an essential practice for crops in this rotation system. However, the recommended application rates for liming materials in some prefectures in Japan are generally low (typically not exceeding 1.5 t $ha^{-1}$), making it difficult to manage and maintain both soil pH and exchangeable cation contents. Given that measuring soil pH in both the laboratory and the field is easier than elemental analysis, the primary practical objective of liming in paddy-upland rotation fields is to improve soil pH rather than maintain exchangeable cation content.

## Conclusion and future perspectives

This review summarizes the findings of previous research by Takamoto et al. on the effects of liming materials on soybean growth and yield in paddy-upland rotation fields with an emphasis on exchangeable cation content. The studies mentioned show that, within this cultivation system, managing both soil pH and exchangeable cation content with liming materials is important for improving soybean yield. However, the detailed mechanisms underlying the effects of liming remain unclear. Studies on the application of liming materials to crops, including soybean, in paddy-upland rotation systems are limited in Japan, and further research is needed to explore this possibility.

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