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Sugar Processing Residuals as an Iron Source for Grain Crops Grown in Calcareous Soil

Shahrzad Karami\textsuperscript{a,b}, Jafar Yasrebi\textsuperscript{a}, Sedigheh Safarzadeh Shirazi\textsuperscript{a}, Joann K. Whalen\textsuperscript{b}, Abdolmajid Ronaghi\textsuperscript{a}, and Reza Ghasemi-Fasaei\textsuperscript{a}

\textsuperscript{a}Department of Soil Science, School of Agriculture, Shiraz University, Shiraz, Iran; \textsuperscript{b}Department of Natural Resource Sciences, Macdonald Campus, McGill University, Montreal, Canada

Abstract
Iron (Fe) deficiency is common when grain crops are grown in calcareous soils. The study was conducted to determine if the DTPA-extractable Fe concentration and Fe uptake of sorghum and corn were greater when Fe fertilizers were co-applied with sugar processing residuals than without residuals. The glasshouse pot experiment was a $3 \times 3 \times 3$ complete factorial with three Fe fertilizer sources (none, 5 mg Fe kg\textsuperscript{-1} of FeSO\textsubscript{4}, 5 mg Fe kg\textsuperscript{-1} of Fe-EDDHA (Fe-ethylene diamine-N,N\textsuperscript{-}bis (2-hydroxyphenylacetic acid)) combined with three residuals (filtercake, bagasse and sugar beet) that were applied at rates of 0, 1.5 and 3\% (w/w) and cropped continuously with sorghum-sorghum-corn. Cumulative shoot Fe uptake was greater in pots amended with filtercake and sugar beet than bagasse. Application of 3\% bagasse reduced the cumulative shoot Fe uptake by 36\%, compared to the unamended control ($P<.05$). Application of Fe-EDDHA or FeSO\textsubscript{4} increased cumulative shoot Fe uptake by 9\%, compared to the unfertilized control. The DTPA-extractable Fe concentrations were consistently higher in soil amended with filtercake and Fe-EDDHA, and declined with time. Since co-application of Fe fertilizer and residuals did not increase Fe uptake, this practice is not expected to improve Fe availability in calcareous soils. Filtercake and sugar beet residuals are alternative Fe sources for grain crops in calcareous soils.

Introduction
Iron (Fe) concentration is inherently low in calcareous soils due to the high pH level and calcium carbonate content. Inadequate soil Fe concentration is responsible for 15–25\% of the yield loss in grain crops like sorghum and corn grown in calcareous soils (Godsey et al. 2003; Westfall and Bauder 2011). While foliar Fe fertilizers may alleviate Fe deficiency symptoms in affected crops, the recommended application rates of foliar fertilizers are too low to meet the Fe requirements of grain crops. The only way to increase the soil Fe concentration is by applying Fe fertilizers to soil. Still, many farmers find it expensive to apply Fe fertilizers to calcareous soils and are uncertain about the efficacy of this practice. Cheaper Fe sources like FeSO\textsubscript{4} $\bullet$ 7H\textsubscript{2}O form insoluble precipitates of FeCO\textsubscript{3} within 1 to 30 d of application to calcareous soils (Goos and Germain 2001; Heydari, Samar, and Moez-Ardalan 2015; Koenig and Kuhns 2002). In a field with a calcareous sandy-loam soil (pH 8.4), the Fe nutrition of sorghum was improved in the first year after 2.8 t ha\textsuperscript{-1} of FeSO\textsubscript{4} $\bullet$ 7H\textsubscript{2}O was applied, but no improvement in Fe nutrition was observed in the second growing season (Mathers 1970). Iron chelates such as Fe-ethylene diamine-N,N\textsuperscript{-}bis (2-hydroxyphenylacetic acid), commonly referred to as Fe-EDDHA, are less susceptible to precipitation and therefore expected to be more
efficient Fe fertilizers. However, the price of Fe-EDDHA is nearly two orders of magnitude greater than Fe salts, based on a selling price of 2000 to 5000 US$ per metric ton for Fe-EDDHA, compared to 85 to 98 US$ per metric ton for FeSO$_4$ • 7H$_2$O (Chen et al. 2016).

Applying organic residuals, alone or in combination with inorganic Fe fertilizers, could increase soil DTPA-extractable Fe concentration and Fe uptake by grain crops in calcareous soils. Plant-based residuals contain soluble Fe within their cells and Fe-rich compounds such as heme proteins that release Fe gradually during decomposition and mineralization processes. Decomposition of plant-based residuals also releases H$^+$ and organic acids, which cause a temporary, localized acidification of the pH in calcareous soils (Lindsay 1991; McCauley, Jones, and Olson-Rutz 2017) and Fe availability is greater in acidic than alkaline micro-environments. In addition, organic acids from decomposing plant-based residuals can dissolve FeCO$_3$ precipitates (Lindsay 1991) or act as chelating agents for Fe (Lanna et al. 2018). Other ways that plant-based residuals can influence Fe biogeochemical cycling is by increasing the soil organic matter content and cation exchange capacity (Barbosa et al. 2012), which may promote Fe exchange between the solid and solution phases. Greater Fe mobilization is expected with higher soil organic matter levels, according to Morris, Loeppert, and Moore (1990), who grew three soybean varieties in 23 calcareous soils with variable clay, Fe oxide, CaCO$_3$, and organic matter contents.

Co-application of Fe fertilizers with fresh or composted animal manure can increase the soil DTPA-extractable Fe concentration significantly (Heydari, Samar, and Moez-Ardalan 2015; Mann et al. 1978; Shenker and Chen 2005; Thomas and Mathers 1979). This occurs because Fe in urine and feces contributes to the soil DTPA-extractable Fe pool. Although co-application of FeSO$_4$ and peat was beneficial to tomatoes, roses, and pot plants (Chen and Barak 1982), there is little information on how co-application of Fe fertilizer and other plant-based residues affects the soil DTPA-extractable Fe concentration, immediately and after several cropping cycles.

Sugar processing residuals such as filtercake, bagasse and sugar beet are expected to increase Fe uptake by crops in calcareous soils because they contain Fe and organic matter. Calcareous soils amended with sugar processing residuals have lower soil pH (Jamil Khan 2011) and more cation exchange capacity (Dotaniya et al. 2016; Prado, Caione, and Campos 2013). Specifically, Campiteli et al. (2018) found that application of 40 to 60 t ha$^{-1}$ of filtercake increased the cation exchange capacity by 57% compared to the unamended control in a five-year soybean-sugarcane cropping sequence. Consequently, application of sugarcane residuals (8% w/w, equivalent to 160 t ha$^{-1}$) to a calcareous soil increased the extractable Fe concentration significantly between 0 and 35 d in plant-free soil incubated at field capacity (Shenker and Chen 2005). Changes in the soil DTPA-extractable Fe concentration in the presence of a crop still need to be assessed in calcareous soils that receive Fe fertilizers with and without sugar processing residuals.

The objective of this study was to investigate how soil DTPA-extractable Fe concentration and crop Fe uptake were affected by the application of Fe fertilizers (FeSO$_4$ and Fe-EDDHA) and sugar processing residuals (filtercake, bagasse and sugar beet), which were applied alone or together. It is hypothesized that crop Fe uptake will be greater when sugar processing residuals are applied alone or in combination with FeSO$_4$ than the time when no residual is applied. Also, the soil DTPA-extractable Fe concentration will increase with time when Fe fertilizer is co-applied with sugar processing residuals than the time when no residual is applied. These hypotheses were tested in glasshouse pots containing calcareous soil that received a single application of Fe fertilizer × sugar processing residual treatments. Soils were cropped continuously with sorghum-sorghum-corn for 210 d during a 270 d experimental period.

**Materials and methods**

**Soil and sugar processing residuals**

A calcareous soil (Chitgar series, Fine-loamy, carbonatic, thermic, Typic Calcixerept) was obtained from the 0–20 cm layer of an unfertilized, fallow field in Sarvestan, Fars, Iran (29°16′25″N; 53°13′13″E). It was air-dried, sieved (<2 mm) and homogenized, then analyzed for baseline physico-chemical properties (Table 1). Sugar processing residuals were supplied by Eghlid sugar beet and Dehkhoda sugarcane.
factories, Fars and Ahvaz Provinces, Iran. Sugar beet and sugarcane (bagasse) residuals were dried by the factory. Sugar beet was more cellulosic and bagasse was more fibrous, so they had different C:N ratios (Table 2). Filtercake is a residue collected after the treatment of sugarcane juice by filtration, which has a low C:N ratio (Table 2). Residuals were ground and sieved (<2 mm) before use.

### Glasshouse experiment

The glasshouse experiment was a $3 \times 3 \times 3$ factorial arranged in a completely randomized design with three replicates per treatment, for a total of 81 pots. The first factor was Fe fertilizer, with the following treatments: no-fertilizer control, 5 mg Fe kg$^{-1}$ as FeSO$_4 \cdot 7$H$_2$O containing 19.7% Fe and 5 mg Fe kg$^{-1}$ of Fe-EDDHA chelate containing 6% Fe. The FeSO$_4 \cdot 7$H$_2$O was purchased from Merck Company, Germany and the Fe-EDDHA was obtained from Syngenta Company, Spain. The second factor was the sugar processing residuals, hereafter referred to as ‘residuals’ in the text: filtercake, bagasse and sugar beet. The third factor was the residual application rate, which was 0% (control), 1.5% w/w or 3% w/w. The 1.5% and 3% application rates are equivalent to 30 and 60 t ha$^{-1}$, which are recommended agronomic rates for plant-based residuals in this area.

Pots (19.3 cm in height and 22 cm in diameter) were prepared by taking 5 kg of dry soil, adding the Fe fertilizer and residuals to the soil, and mixing it completely. Basal nutrients (except for Fe) were applied according to the soil test results, to prevent possible nutrient deficiency, and incorporated uniformly by re-mixing the soil. Then, six seeds of sorghum (Sorghum bicolor (L.) Moench cv. KFS-2) were planted in the dry soil, pots were irrigated to field capacity with distilled water, and the weight was recorded. Soil moisture was maintained at field capacity by watering every day with distilled water to a constant weight, accounting for biomass accumulation during the experiment. After 10 d, seedlings were thinned to three plants pot$^{-1}$. Glasshouse conditions were 10–25°C with

### Table 1. Selected physical and chemical characteristics of a calcareous soil, from Sarvestan, Fars Province, Iran.

<table>
<thead>
<tr>
<th>Soil characteristic</th>
<th>unit</th>
<th>amount</th>
<th>Soil characteristic</th>
<th>unit</th>
<th>amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>g kg$^{-1}$</td>
<td>220</td>
<td>Total N</td>
<td>g kg$^{-1}$</td>
<td>1.16</td>
</tr>
<tr>
<td>Silt</td>
<td>g kg$^{-1}$</td>
<td>460</td>
<td>Available P</td>
<td>mg kg$^{-1}$</td>
<td>12.4</td>
</tr>
<tr>
<td>Clay</td>
<td>g kg$^{-1}$</td>
<td>320</td>
<td>Exchangeable K (Ammonium acetate method)</td>
<td>mg kg$^{-1}$</td>
<td>420</td>
</tr>
</tbody>
</table>

- Soil chemical and physical properties were determined with standard methods (Sparks et al. 1996).

### Table 2. Selected chemical characteristics of sugar processing residuals used in the glasshouse study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Zn$^b$</th>
<th>Fe$^b$</th>
<th>Mn$^b$</th>
<th>Cu$^b$</th>
<th>Total N</th>
<th>P$^c$</th>
<th>K$^d$</th>
<th>Electrical conductivity (EC)$^e$</th>
<th>pH$^e$</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtercake</td>
<td>60.3</td>
<td>74.5</td>
<td>66.8</td>
<td>9.03</td>
<td>28.2</td>
<td>945</td>
<td>6323</td>
<td>4.9</td>
<td>7.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Bagasse</td>
<td>27.3</td>
<td>859</td>
<td>33.8</td>
<td>3.58</td>
<td>3.94</td>
<td>359</td>
<td>1680</td>
<td>1.1</td>
<td>8.6</td>
<td>120</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>14.4</td>
<td>150</td>
<td>35.8</td>
<td>5.13</td>
<td>19.3</td>
<td>282</td>
<td>14571</td>
<td>1.9</td>
<td>6.6</td>
<td>42.5</td>
</tr>
</tbody>
</table>

- Chemical properties of sugar processing residuals were determined with standard methods (Sparks et al. 1996).
- DTPA-extractable Zn, Fe, Mn and Cu concentrations in filtercake, and total Zn, Fe, Mn and Cu concentrations in bagasse and sugar beet residuals.
- Available P in filtercake, and total P in bagasse and sugar beet.
- Exchangeable K in filtercake, and total K in bagasse and sugar beet.
- Determined in a 1:10 suspension of sugar processing residual:water.
10 h:14 h of daylight:night. After 10 wk, the shoots were harvested, rinsed with distilled water, dried at 65°C for 48 h to determine the dry weight, then ground (<1 mm mesh) and dry ashed at 550°C.

Following the first sorghum harvest, soil was taken out of the pot, dried, visible roots were removed, then it was mixed, sieved (<2 mm) and sampled. Pots (17.8 cm in height and 19 cm in diameter) were prepared again by taking 4 kg of the remaining soil. According to the soil test, nitrogen (200 mg kg$^{-1}$ from urea (CO(NH$_2$)$_2$) source) and phosphorus (10 mg kg$^{-1}$ from CaH$_4$(PO$_4$)$_2$ • H$_2$O source) were mixed uniformly in all pots to prevent nutrient deficiencies in the next crop. There was a 2 wk interval between the first harvest and planting the next crop. Six seeds of the same sorghum variety were planted in each pot and thinned to three plants pot$^{-1}$ by 10 d after emergence, following the same procedures and watering regime as the first sorghum crop. Glasshouse conditions were 15–35°C with 12 h:12 h of daylight:night. After 10 wk, the shoots were harvested, rinsed with distilled water, dried at 65°C for 48 h to determine the dry weight, then ground (<1 mm mesh) and dry ashed at 550°C.

After the second sorghum harvest, roots were removed, soil was dried, remixed, sieved (<2 mm) and sampled. Pots (16.8 cm in height and 19.5 cm in diameter) were then prepared with 3 kg of the remaining soil. Basal nutrients required for this cultivation were nitrogen (200 mg kg$^{-1}$ from urea (CO(NH$_2$)$_2$) source) and phosphorus (10 mg kg$^{-1}$ from CaH$_4$(PO$_4$)$_2$ • H$_2$O source), which were mixed uniformly in all pots before planting six corn seeds (Zea mays L. cv. Single cross 704). Thinning and watering procedures were the same as the first and second cultivations. Glasshouse temperatures were 15–45°C with 14 h:10 h of daylight:night. After 10 wk, the shoots were harvested, rinsed with distilled water, dried at 65°C for 48 h to determine the dry weight, then ground (<1 mm mesh) and dry ashed at 550°C. Soil samples were collected after root removal, air-drying and sieving (<2 mm).

**Analysis of plant and soil samples**

One gram of ashed shoot tissue was solubilized in 5 mL of 2 N hydrochloric acid and the contents of the crucible were filtered (Whatman 42) with hot distilled water and transferred into a 50 mL volumetric flask. The Fe concentration was measured using atomic absorption spectroscopy (Shimadzu, AA-670 model, Japan) and shoot Fe uptake (mg Fe) was the shoot Fe concentration (mg Fe g$^{-1}$) × shoot dry weight (g). The cumulative shoot Fe uptake (mg Fe pot$^{-1}$) was the sum of the Fe uptake by the successive sorghum-sorghum-corn crops. Soil Fe concentration (mg DTPA-extractable Fe kg$^{-1}$ dry soil) was determined in DTPA extracts (Lindsay and Norvell 1978). Soil pH was determined in 1:5 ratio (soil:water) extract before the first crop (after treatments were applied) and after each crop harvest. The amount of organic carbon input (g C pot$^{-1}$) was the percentage of organic carbon in each type of residuals × residual rates used for each pot (g residual pot$^{-1}$).

**Statistical analyses**

The effect of Fe fertilizers, residual type and residual application rate on the soil DTPA-extractable Fe concentration, shoot Fe uptake and cumulative shoot Fe uptake by successive sorghum-sorghum-corn crops were analyzed by three-way analysis of variance. Cumulative shoot Fe uptake and soil DTPA-extractable Fe concentration were affected significantly ($P < .05$) by the residual type, residual application rate and their interaction, so data was pooled among Fe fertilizers and the means of each residual type × application rate (n = 9) were compared with appropriate statistical tests (Tukey’s Studentized Range (HSD) or LSD) at the 95% confidence level. Changes in soil DTPA-extractable Fe concentration in soils amended with residuals or Fe fertilizers, relative to the control that received no Fe fertilizer or no residual, during the experimental period were fitted with linear or exponential relationships. Correlations between shoot Fe uptake and soil DTPA-extractable Fe concentration, soil pH and organic carbon input were determined with Pearson correlation analysis (n = 81).
Results

Iron uptake in sorghum and corn

Cumulative shoot Fe uptake by the successive sorghum-sorghum-corn crops was greater in pots amended with filtercake and sugar beet than bagasse (P < .05, Table 3), due to the significant (P < .05) decline in cumulative shoot Fe uptake with the 3% bagasse treatment (Figure 1). During the experimental period, there was 9% more cumulative shoot Fe uptake by sorghum and corn grown in pots receiving FeSO₄ and Fe-EDDHA fertilizers than in pots that received no Fe fertilizer (Table 3).

Iron concentration in plant leaves were in sufficiency range (55–200 mg Fe kg⁻¹) in the first and second sorghum planting but it was marginally sufficient (50–59 mg Fe kg⁻¹) in corn leaves (Jones, Wolf, and Mills 1991), However, there was no visual sign of iron chlorosis. Soil pH was negatively correlated with shoot Fe uptake (r = −0.28, P = .05, n = 81, Figure 2), and lower pH values were associated with residual-amended soils. Cumulative shoot Fe uptake did not change with increasing organic C input.

Table 3. Cumulative shoot Fe uptake by successive sorghum-sorghum-corn grown in pots amended with Fe fertilizer mixed with sugar processing residuals (residual) at three application rates (rate). Values in the main table are the mean ± standard error (n = 3). The mean effects of Fe fertilizer (n = 27, pooled amongst residuals and rates) and sugar processing residuals (n = 27, pooled among Fe fertilizers and rates) were compared with a LSD test (P < .05).

<table>
<thead>
<tr>
<th>Fe fertilizer</th>
<th>Residual application rates (% w/w)</th>
<th>Filtercake (mg pot⁻¹)</th>
<th>Bagasse (mg pot⁻¹)</th>
<th>Sugar Beet (mg pot⁻¹)</th>
<th>Mean effect of Fe fertilizer (mg pot⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>3.1 ± 0.1</td>
<td>3.0 ± 0.2</td>
<td>3.0 ± 0.1</td>
<td>3.3 ± 0.1 Bᵃ</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3.6 ± 0.2</td>
<td>2.8 ± 0.4</td>
<td>4.1 ± 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.0 ± 0.0</td>
<td>2.2 ± 0.1</td>
<td>3.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>FeSO₄</td>
<td>0</td>
<td>3.8 ± 0.3</td>
<td>3.9 ± 0.1</td>
<td>3.8 ± 0.2</td>
<td>3.6 ± 0.1 A</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3.9 ± 0.1</td>
<td>3.0 ± 0.2</td>
<td>4.1 ± 0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.5 ± 0.6</td>
<td>2.3 ± 0.3</td>
<td>3.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Fe-EDDHA</td>
<td>0</td>
<td>4.0 ± 0.4</td>
<td>3.7 ± 0.3</td>
<td>3.8 ± 0.1</td>
<td>3.6 ± 0.1 A</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3.7 ± 0.2</td>
<td>3.8 ± 0.5</td>
<td>3.9 ± 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.7 ± 0.1</td>
<td>2.2 ± 0.1</td>
<td>3.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>Mean effect of sugar processing residual</td>
<td>3.8 ± 0.1 A</td>
<td>3.0 ± 0.1 B</td>
<td>3.7 ± 0.1 A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ᵃMeans with different letters are significantly different (P < .05, LSD test).

Figure 1. Cumulative shoot Fe uptake by successive sorghum-sorghum-corn grown in pots amended with sugar processing residuals at three application rates. Values are the mean with standard error bars (n = 9, pooled among Fe fertilizer treatments). Means with different letters are significantly different (P < .05, HSD test).
from most residuals, whether applied alone or in combination with Fe fertilizer, although it declined in the soil receiving Fe fertilizer co-applied with bagasse ($r = -0.74, P = 0.01, n = 12$, Figure 3).

**Soil DTPA-extractable Fe**

By the end of the experimental period, there was 67% more soil DTPA-extractable Fe remaining in the 3% filtercake treatment than the control without fertilizer and residuals, which was significantly ($P < 0.05$) greater than the other residual types and application rates (Figure 4). The soil DTPA-extractable Fe concentration declined linearly in the residual-amended soils, at a rate of about 0.001 mg DTPA-extractable Fe kg\(^{-1}\) d\(^{-1}\) (Figure 5a). Soils that received Fe-EDDHA also had less soil DTPA-extractable Fe with time, according to a negative quadratic model, but those fertilized with FeSO\(_4\) had less soil DTPA-extractable Fe throughout the experimental period (Figure 5b). The soil DTPA-extractable Fe concentration was as high as 8 mg DTPA-extractable Fe kg\(^{-1}\) after the first harvest and declined to <1.5 mg DTPA-extractable Fe kg\(^{-1}\) after the third harvest (Figure 6). Soil DTPA-extractable Fe was positively correlated with shoot Fe uptake in sorghum and corn crops during the study ($r = 0.37, P = 0.01, n = 81$, Figure 6).

**Discussion**

It was hypothesized that crop Fe uptake will be greater when sugar processing residuals are applied alone or in combination with FeSO\(_4\) than when no residual is applied. Application of filtercake and sugar beet residuals tended to improve shoot Fe uptake, but application of 3% bagasse reduced cumulative shoot Fe uptake and should be avoided (Table 3, Figure 1). Co-application of residuals and Fe fertilizers did not improve the cumulative shoot Fe uptake (Table 3). Sugar processing residuals were expected to be a source of Fe, immediately after application or following their decomposition. Filtercake seems to be an immediate source of Fe since it contained more DTPA-extractable Fe than sugar beet or bagasse. Sugar beet also appears to release Fe immediately after its application based on the similar pattern of shoot Fe uptake in sugar beet-amended soils. However, bagasse did not release an appreciable amount of Fe after its application or following decomposition. This is consistent with field research suggesting that bagasse is a slow-release fertilizer. For instant, Bijan Pour et al. (2010) recommended applying bagasse at least three months before planting.
sugarcane because it did not produce as much yield as filtercake, even when more bagasse was applied (60 t bagasse ha$^{-1}$ vs. 40 t filtercake ha$^{-1}$).

Another way that sugar processing residuals may affect soil Fe fertility is by reducing soil pH and increasing CEC or soil organic matter content. Lower soil pH was associated with higher cumulative shoot Fe uptake.

**Figure 3.** Relationship between cumulative shoot Fe uptake and organic carbon (C) input ($n = 81$). The dotted line is the Pearson correlation coefficient ($r$) between cumulative shoot Fe uptake and organic carbon input in soil co-applied with Fe fertilizers + bagasse.

**Figure 4.** Soils DTPA-extractable Fe concentration after successive sorghum-sorghum-corn were grown in pots amended with sugar processing residuals at three application rates (measured at the end of the experiment and after corn harvest). Values are the mean with standard error bars ($n = 9$, pooled among Fe fertilizer treatments). Means with different letters are significantly different ($P < .05$, HSD test).
Fe uptake in this study, which is consistent with the proposed mechanism. The CEC and organic matter content was not measured at the end of the study, so it is not known how these parameters may have influenced Fe bioavailability. However, cumulative shoot Fe uptake was negatively correlated to the organic C input in bagasse-amended soils and not affected by the organic C input in soils receiving filtercake and sugar beet residuals (Figure 3). Therefore, adding organic matter is not expected to increase Fe bioavailability in this calcareous soil.

We predicted an increase in soil DTPA-extractable Fe concentration with time when Fe fertilizer is co-applied with sugar processing residuals than when no residual is applied. This was not true, since soil DTPA-extractable Fe concentration decreased with time in all treatments (Figure 5a,b). Overall, the DTPA-extractable Fe concentration was weakly related to the cumulative shoot Fe uptake. Although the DTPA-extractable Fe concentration was consistently soil amended with FeSO₄ than Fe-EDDHA (Figure 5b), there was no difference in the cumulative shoot Fe uptake in these treatments (Table 3). Furthermore, filtercake-amended soil has more DTPA-extractable Fe than sugar beet residuals (Figure 5a), but the cumulative shoot Fe uptake was equivalent for filtercake and

---

**Figure 5.** Change in soil DTPA-extractable Fe concentration with time in soil amended with sugar processing residuals (a) and Fe fertilizers (b). Values are the mean with standard error bars of n = 18 (pooled among residual rate and Fe fertilizer in panel (a)) or n = 27 (pooled among residual type and rate in panel (b)).
sugar beet treatments (Table 3). Under the experimental conditions in this study, the plant bioassay was a superior indicator of bioavailable Fe than the soil DTPA-extractable Fe concentration.

Based on the lower Fe concentration in corn leaves than sorghum and the decline in DTPA-extractable Fe from the first to third cultivation, it appears that the bioavailable Fe pool was depleted during this study. Regular Fe fertilization is recommended for calcareous soils in this region. In addition to Fe-EDDHA, other suitable Fe fertilizers would be FeSO₄, filtercake and sugar beet residuals. These sugar processing residuals may provide other positive effects on soil fertility (such as increasing the amount of soil organic carbon and adding other macro and micronutrients). Application of filtercake and sugar beet residuals to agricultural land is recommended as a solution for residual management, and they could be promoted as a Fe source for grain crops grown in calcareous soils.

**Conclusions**

Application of Fe-EDDHA or FeSO₄ can improve Fe fertility in calcareous soils compared to no Fe fertilizer application. Sugar processing residuals such as filtercake and sugar beet can be good alternatives to expensive Fe fertilizers since they improved the Fe uptake by sorghum and corn crops. Bagasse is not suitable as a Fe source and should not be used for this purpose. Co-application of sugar factory residuals and Fe fertilizers did not increase Fe uptake, so co-applying these residuals is not expected to improve Fe fertility in calcareous soils.

**Acknowledgments**

Eghlid and Dehkhoda sugar factories are acknowledged for the donation of residuals.

**Conflicts of Interest**

The authors declare no conflicts of interest.