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Evaluating efficacy of organo-mineral fertiliser to meet nutrient demands of cereal crops in England

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A B S T R A C T

Whilst mineral fertilisers are a reliable source of crop nutrients in conventional arable farming, their production is associated with significant environmental and economic challenges, including greenhouse gas emissions, price volatility, and nutrient leaching. Organo-mineral fertilisers (OMFs) have been proposed as a sustainable alternative, combining mineral nutrients with organic residues. This study investigated the potential of OMFs to supplement mineral fertiliser applications in arable farming across three field trials in England from 2022 to 2023. The trials examined the impact of an OMF derived from composted food waste added to potassium chloride and ammonium sulfate (8–3-3 + 19% SO_3) on soil nutrient dynamics, grain yield, and crop quality in spring barley (*Hordeum vulgare*) and oats (*Avena sativa*). The results indicated that OMF application increased soil sulphur levels at two sites, suggesting its potential as a sulphur source for cereal crops. However, grain nutrient concentrations showed minimal response to OMF treatments compared to mineral fertilisers, with only minor differences observed in phosphorus, sulphur, and zinc levels. Yield responses varied by site, with OMF application resulting in slight reductions in barley grain and nitrogen yields compared to mineral fertiliser, particularly at higher nitrogen application rates. The oat trial showed no significant fertiliser effects, likely due to high inherent soil fertility and potential nutrient leaching. These findings highlight that while OMFs can contribute to nutrient cycling and sustainable fertiliser management, their effectiveness depends on formulation, nutrient release patterns, and site-specific factors such as soil fertility and weather conditions. The quality and composition of organic feedstocks within OMFs are critical to ensuring optimal synchronisation of nutrient availability with crop requirements, supporting their role in integrated nutrient management programs.

1. Introduction

Conventional arable farming has long relied on the application of mineral fertilisers to achieve high crop yields. This is feasible as mineral fertilisers are well characterised and traceable, allowing us to utilise their stoichiometry to predict nutrient availability to crops. While effective in providing readily available nutrients to crops, this practice is associated with many undesirable environmental outcomes. Fertiliser production generates significant greenhouse gases (GHGs) globally (Menegat et al., 2022), but a substantial range of emission intensity can be found, from natural gas based operations in Europe (1.6 t CO_2/t NH_3) to coal-powered in China (4.5 t CO_2/t NH_3) (Lin et al., 2023). The price of mineral fertilisers is also closely tied to global energy prices, making farmers vulnerable to price fluctuations (Jones and Deuss, 2024). The excessive use of mineral fertilisers can also lead to nutrient leaching of N and P into water bodies, causing eutrophication and harm to aquatic ecosystems (Withers and Haygarth, 2007). These environmental and economic challenges highlight the urgent need for more sustainable approaches to plant nutrition and fertiliser application.

Alternative sources of plant nutrition, such as leguminous crop rotations, livestock manure, anaerobic digestate, biosolids and compost, have been explored as potential substitutes for mineral fertilisers. These methods can contribute valuable organic matter and nutrients to the soil. However, they are often insufficient to meet the nutrient demands of high-yielding arable crops, particularly in low-income countries where conventional fertiliser use is low (Falconnier et al., 2023). The supply of organic nutrients is also often far away from arable farms, particularly in the UK, where livestock farms predominate the west of the country whilst arable farms predominate the east (Angus et al., 2009). Organic fertilisers may also introduce their own environmental challenges, such as greenhouse gas emissions from manure management (Charles et al., 2017), inconsistency in its nutrient content due to inherent variation in feedstocks or the introduction of pathogens and heavy metals through organic amendments (Chander and Brookes, 1991). To address these issues, it is essential to reduce fertiliser use while maintaining crop yields and simultaneously valorising agricultural residues that contain valuable nutrients and organic matter. This approach not only seeks to minimise environmental impacts but also aims to enhance the sustainability and resilience of agricultural systems.

Organo-mineral fertilisers (OMFs) can facilitate farmers to provide

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crop nutrients and recycle organic materials because they combine both mineral and organic residues (Sakrabani, 2024). The organic component of OMFs can be sourced from crop residues, livestock manure, digestate and food waste, and facilitates the recycling of agricultural residues back into the soil. The mineral component provides nutrients in available form, while the organic component provides organic carbon, which can improve soil structure, enhance microbial activity, and contribute to long-term soil fertility (Pawlett et al., 2021). OMFs can therefore provide some of the essential nutrients required for crop production, but their capacity to supply adequate, and 'sufficiently available' nutrients to crops is limited for several reasons. The European Union has regulated OMF as products which contain no more than 16% N (Commission, 2019), which is much lower than conventional mineral fertiliser (for example, ammonium nitrate is 34% N and urea is 46% N). A farmer looking to provide N for cereals using OMF would therefore require product application rates >1 t ha^{-1}, which may be difficult to do in practice. The mineral component within organic residues may take time to solubilise when bound with recalcitrant organic materials, which can restrict nutrient availability. These limitations imply OMF will not be able to replace mineral fertiliser, but if used in tandem with mineral fertiliser, the provision of organic materials and some mineral N by OMF may still mitigate dependence on mineral fertiliser and play a role in sustainable nutrient management programs.

OMF and mineral fertilisers working in tandem may also help to resolve global nutrient imbalances, for example by transferring nutrients from intensive livestock operations to arable land. Research by Deeks et al. (2013), Pawlett et al. (2015), Antille et al. (2017) reported that when using OMFs derived from biosolids, crop yields of combinable crops were not compromised when compared to mineral fertilisers, which is encouraging. Burak and Sakrabani (2023) reported similar finding when using OMF derived from crop residue and animal manure as part of a carbon capture technology. These studies show that the quality of organic feedstock within OMFs is vital in influencing its reliability as a fertiliser to meet crop nutrient requirements.

The properties of OMFs can vary significantly depending on the ratio of mineral to organic components and the specific materials used. The type of mineral fertiliser incorporated, the choice of organic waste material and the ratio of organic-to-mineral components can influence nutrient release patterns. The carbon-to-nitrogen (C:N) ratio of the organic component of the OMF can also impact the nutrient release rate of the OMF. The C:N ratio is particularly important as it can affect soil nutrient cycling by influencing the mineralization and immobilization of nutrients, which determines the availability of nutrients for crop uptake (Qian and Schoenau, 2002). Different OMF feedstocks can have various C:N ratios, and lability of C within the biomass. The different kinds of organic C found in potential OMF feedstocks can be either labile or recalcitrant (Fischer et al., 2018) and therefore variable rates of decomposition can be expected when these are incorporated into OMF production. All of these can impact on the effectiveness of the OMF, both in the immediate crop production and in the long-term soil health. It is therefore essential that field trials examining different kinds of OMF formulations are carried out to determine the most effective formulations and feedstocks for OMF production.

To investigate the potential of OMFs in arable farming, three experiments were carried out across different locations in England from 2022 to 2023. These experiments included two different crops and compared the effect of OMF and mineral fertilisers on crop performance and soil quality. A comprehensive survey of soil health metrics was recorded at the end of each experiment, along with measurements of grain yield and quality.

This study aims to evaluate the effectiveness of OMFs as a viable component of sustainable nutrient management programs in arable farming. The hypothesis is given below. It assumes the application rates (kg N ha^{-1}, not kg product ha^{-1}) of OMF and mineral fertiliser are the same

Hypothesis. When applied on an equivalent nitrogen basis, substituting mineral fertiliser with OMF will result in crop performance, soil nutrient and soil health outcomes that are comparable to those achieved using mineral fertiliser alone. This hypothesis is evaluated across different substitution strategies, including partial or full replacement and different application timings, using evaluations of grain yield, nitrogen uptake, soil nutrients and soil health metrics.

2. Methods

Three field trials were carried out in 2022 and 2023 in England. Site information is given in Table SM1. Fertiliser treatment application descriptions are given in Table SM2. Weather information is given in Figure SM1. A randomised block design was used in all sites.

2.1. Market Weighton

Two fertiliser treatments with incremental N rate application rates were applied to the spring barley (*Hordeum vulgare*) at Market Weighton. The mineral fertiliser selected was a compound mineral NPKS fertiliser produced by YARA known as 52 s. 52S is a contains nitrogen, phosphate, potash and sulphur (20.6% Nitrogen, 8.2% Phosphate, 11.6% Potash, 6.5% Sulphur Trioxide) and is prilled during manufacturing to ensure equal nutrient density in all fertiliser granules. The OMF selected was a pellet derived from composted food waste added to potassium chloride and ammonium sulfate (8% Nitrogen, 3% Phosphate, 3% Potash and 19% Sulphur Trioxide). The dry matter was 92% and the C content was 25%. A control treatment in which no fertiliser was also included. The C content of the OMF was 25% and the dry matter content was 92%. This OMF was used in all three trials. Both fertilisers were applied in the same incremental kg N ha^{-1} rates. An initial seedbed of 40 kg N ha^{-1} was applied and then rates of 40, 80, 120, 160, 200 kg N ha^{-1} were applied to individual plots at GS13 (Zadoks et al., 1974). Application rates are summarised in Table SM2. Soil samples were taken for soil health metrics at GS30, GS39 and at final harvest. Soil samples were taken with a Dutch auger to a depth of 10 cm. This sampling strategy was also used in all other trials.

All plots were sampled for soil P, K and Mg, but only the 160 kg N ha^{-1} and fertiliser split was sampled for the other assessed soil nutrients (B, Ca, Cu, Fe, Mn, Mo, Na, S, Zn). Other soil health metrics including pH, soil organic matter, soil respiration, total N, C:N ratio, microbial biomass, potentially mineralisable N, cation exchange capacity and soil organic carbon were also assessed on samples from each fertiliser and 160 kg N ha^{-1} interaction only. Soil biological activity was assessed using the Solvita® soil respiration test, which estimates microbial respiration as CO_2–C evolved (mg CO_2 kg^{-1} soil day^{-1}) from rewetted soil during a 24-h incubation period. Leaf samples were also taken from the spring barley at GS13 and GS39 from the fertiliser and 160 kg N ha^{-1} interaction only and assessed for the following nutrients: Ca, Mg, Mn, B, Cu, Mo, Fe, Zn, S, P, K and N. Grain yield was assessed for all treatment interactions using a plot combine at final harvest and grain nutrients (N, P, K, S, Mg) were assessed for all fertiliser and 160 kg N ha^{-1} interactions. All soil, leaf and grain quality analyses were carried out by Lancrop, a commercial lab based in the UK.

2.2. Felixstowe

This trial examined the effects of early applications of OMF at the seedling stage for spring barley (*Hordeum vulgare*). A seedbed application of 40 kg N ha^{-1} was applied as either 52 s or OMF, and then rates of

40, 80, 120, 160, 200 and 240 kg N ha^{-1} as ammonium nitrate (AN) exclusively was applied to both seedbed treatments (mineral fertiliser and OMF) at GS13. Application rates are summarised in Table SM2. A control treatment in which no fertiliser was also included. Soil health metrics were assessed at final harvest. The soil nutrients assessed were B, Ca, Cu, Fe, K, Mg, Mn, Mo, Na, P, S, and Zn. Soil health metrics including pH, cation exchange capacity total nitrogen, and soil organic matter were also included. Only the control and 160 kg N ha^{-1} treatment for all fertilisers were assessed for soil health. Grain yield was assessed using a plot combine. Grain quality was assessed through the following: protein, B, Ca, Cu, Fe, K, Mg, Mn, Mo, N, P, S, and Zn. All N application rates were incorporated in the grain yield and quality assessments.

2.3. Hingham

This trial also only looked at the effect of OMF applications in the early growth stage for oats (*Avena sativa*). 40 kg N ha^{-1} of mineral fertiliser or OMF was applied at seedbed. The mineral fertiliser used was 52 s. Additional mineral fertilisers in the form of AN were then applied to all previous treatments (mineral fertiliser and OMF) at N application rates of 0, 40, 60, 80, 120 and 140 kg ha^{-1}. Application rates are summarised in Table SM2. A control treatment in which no fertiliser of any kind was also included. Soil health metrics were assessed at final harvest. Soil nutrients assessed were B, Ca, Cu, Fe, K, Mg, Mn, Mo, N, Na, P, S, and Zn. Only the control and 120 kg N ha^{-1} fertiliser splits were assessed for nutrients and soil health metrics. Other soil heath metrics assessed were soil organic matter, pH and cation exchange capacity. Grain yield was assessed using a plot combine. The grain quality metrics assessed were protein, B, Ca, Cu, Fe, K, Mg, Mn, Mo, N, P, S, and Zn. Only the control and 120 kg N ha^{-1} fertiliser splits were assessed for grain quality.

2.4. Statistical analysis

All data analysis was carried out using R (4.3.3). The soil and leaf nutrient data were subjected to ANOVA to evaluate the main effects and interactions of growth stage and fertiliser. Prior to conducting ANOVA, assumptions of normality and homogeneity of variance were assessed. Normality of residuals was examined using QQ plots, and homogeneity of variances was tested using Levene's test. The estimated marginal means were generated using the *emmeans* package to further explore the significant main effects and interactions. Post hoc testing was conducted using the *multcomp* package, with significance letters assigned using Sidak's test to make multiple comparisons. Only significant ($p < 0.05$) interactions are reported in the text.

A linear mixed-effects polynomial model was fitted to assess the effect of fertiliser type and nitrogen application rate on each variate, with block included as a random effect to account for variability between blocks. This model is expressed below as:

$$lmer(Variate \sim Fertiliser * poly(as.numeric(Rate), 2) + (1|Block))$$

where the lmer command runs a mixed model, Variate represents grain yield, nitrogen yield, or nitrogen percentage, and Fertiliser refers to the type of fertiliser applied (mineral fertiliser, OMF, or a combination thereof). The function poly(Rate, 2) denotes a second-degree polynomial for the nitrogen application rate (Rate), allowing for the modelling of both linear and quadratic effects of nitrogen application. The block is included as a random factor within the model. Estimated marginal means were calculated for each 10 kg increment of nitrogen application rate using the *emmeans* package. These estimated marginal means provide model-adjusted predictions of the variate for different fertiliser treatments across the range of nitrogen rates and were plotted using *ggplot2*. Standard errors were also computed and displayed as ribbons around the estimated marginal means. The equations for each plotted curve are given as annotations within the plots. The raw data points were printed behind the fitted curves, with colours corresponding to the fertiliser type. The estimate and p value for each model component were reported in Table 3. Model assumptions were evaluated by inspecting

Table 2
Soil nutrient status at Felixstowe following fertiliser application (units are ppm). Letters indicate statistical significance at $p < 0.05$ using Sidak's test.

Felixstowe	Spring Barley	
	S	Zn
Control	4.25b	5.52a
MF	3b	5.32ab
OMF All	15.5a	4.87ab
OMF Split	3.25b	4.97b
Standard Error	2.41	0.14
p	0.008	0.02

Table 1
Grain nutrient concentrations at Market Weighton, Felixstowe and Hingham. Macronutrients (P, K, S, Mg, Ca) and protein are expressed as % dry matter, while micronutrients (Mn, B, Cu, Mo, Fe, Zn) are expressed as ppm. Letters indicate statistically significant differences at $p < 0.05$ using Sidak's test.

Market Weighton	Spring Barley											
	P	K	S	Mg								
52 s	0.40a	0.78a	0.15b	0.14a								
OMF	0.41a	0.77a	0.15b	0.14a								
Control	0.41a	0.67a	0.12a	0.13a								
Standard Error	0.008	0.029	0.003	0.002								
p	0.55	0.047	0.001	0.14								
Felixstowe	Spring Barley											
	P	K	S	Mg	Mn	B	Cu	Mo	Fe	Zn	Protein	
52 s/Extran	0.34a	0.49a	0.13a	0.10a	11.0a	1.1a	4.0a	1.0bc	50.0a	23.9a	10.4c	
OMF/Extran	0.33a	0.48a	0.14ab	0.10a	9.8a	1.0a	3.7a	0.7b	43.5a	22.8a	9.5bc	
OMF	0.33a	0.49a	0.14ab	0.10a	11.1a	1.0a	3.7a	0.4a	40.2a	22.4a	8.6ab	
Control	0.40b	0.49a	0.12a	0.13b	7.1a	1.2a	4.8a	1.2c	50.1a	30.4b	7.9a	
Standard Error	0.009	0.011	0.003	0.002	1.04	0.08	0.30	0.09	5.86	0.91	0.31	
p	0.001	0.80	0.035	0.001	0.06	0.31	0.059	0.001	0.56	0.001	0.001	
Hingham	Oats											
	P	K	S	Mg	Ca	Mn	B	Cu	Mo	Fe	Zn	Protein
52 s fb Extran	0.43b	0.40a	0.20b	0.13a	0.16a	53.45a	2.0a	4.78a	0.88a	79.7a	40.95a	14.62a
52 s fb Extran + BioNUE	0.41ab	0.39a	0.19b	0.13a	0.15a	54.70a	2.1a	4.83a	0.91a	66.1a	42.20a	14.32a
Control	0.37a	0.36a	0.17a	0.13a	0.15a	55.08a	2.1a	4.70a	1.03a	78.1a	40.98a	12.25a
OMF fb Extran	0.42a	0.39a	0.20b	0.13a	0.16a	53.90a	2.0a	4.70a	0.72a	73.6a	39.53a	14.30a
OMF fb Extran + BioNUE	0.43a	0.40a	0.21b	0.13a	0.16a	59.48a	2.2a	5.00a	0.65a	79.3a	43.15a	13.89a
Standard Error	0.01	0.009	0.004	0.003	0.005	3.24	0.15	0.24	0.08	6.8	1.53	0.58
p	0.003	0.055	0.001	0.79	0.80	0.70	0.92	0.90	0.04	0.59	0.53	0.079

Table 3
Fixed effect estimates and significance values from polynomial mixed-effects models for spring barley (Market Weighton and Felixstowe) and oats (Hingham), showing the effects of fertiliser type and nitrogen application rate on grain yield, nitrogen yield and grain nitrogen percentage.

		Market Weighton Spring Barley		Felixstowe Spring Barley		Hingham Oats	
Parameter	Predictor	Estimate	p	Estimate	p	Estimate	p
Yield (t ha^{-1})	Intercept	14.7192	< 0.001**	9.5875	< 0.001***	6.9273	< 0.001***
Yield (t ha^{-1})	Fertiliser: OMF	-1.4554	< 0.001**	-0.5833	0.01228*	-0.3755	0.0205*
Yield (t ha^{-1})	Rate (poly, 1st component)	7.2768	< 0.001**	7.3951	< 0.001***	0.1894	0.8049
Yield (t ha^{-1})	Rate (poly, 2nd component)	-9.5182	< 0.001**	-3.6107	0.00197**	0.5300	0.4906
Yield (t ha^{-1})	OMF × Rate (poly, 1st component)	1.7960	0.475	-1.4537	0.3507	1.7712	0.1081
Yield (t ha^{-1})	OMF × Rate (poly, 2nd component)	6.2871	0.016*	-1.7899	0.25187	-0.9497	0.3834
Nitrogen (%)	Intercept	1.9096	< 0.001***	1.56833	< 0.001***	2.47375	< 0.001***
Nitrogen (%)	Fertiliser: OMF	-0.1483	< 0.001***	-0.02958	0.477	-0.03250	0.446790
Nitrogen (%)	Rate (poly, 1st component)	2.8676	< 0.001***	2.05203	< 0.001***	0.87642	0.000125**
Nitrogen (%)	Rate (poly, 2nd component)	0.0841	0.643	0.06789	0.738	-0.24071	0.252162
Nitrogen (%)	OMF × Rate (poly, 1st component)	-0.8604	0.002**	0.12086	0.674	0.35327	0.234974
Nitrogen (%)	OMF × Rate (poly, 2nd component)	-0.10493	0.6824	0.40196	0.167	-0.3472	0.9063
N (kg ha^{-1})	Intercept	284.737	< 0.001**	132.307	< 0.001***	77.653	< 0.001***
N (kg ha^{-1})	Fertiliser: OMF	-47.347	< 0.001**	-8.050	0.01228*	-5.348	0.0315*
N (kg ha^{-1})	Rate (poly, 1st component)	528.990	< 0.001**	102.052	< 0.001	27.795	0.0230*
N (kg ha^{-1})	Rate (poly, 2nd component)	-146.156	< 0.001**	-49.828	0.00197*	-10.739	0.3660
N (kg ha^{-1})	OMF × Rate (poly, 1st component)	-109.412	0.051	-20.061	0.3507	27.535	0.1053
N (kg ha^{-1})	OMF × Rate (poly, 2nd component)	111.146	0.048*	-24.701	0.25187	-15.830	0.3463

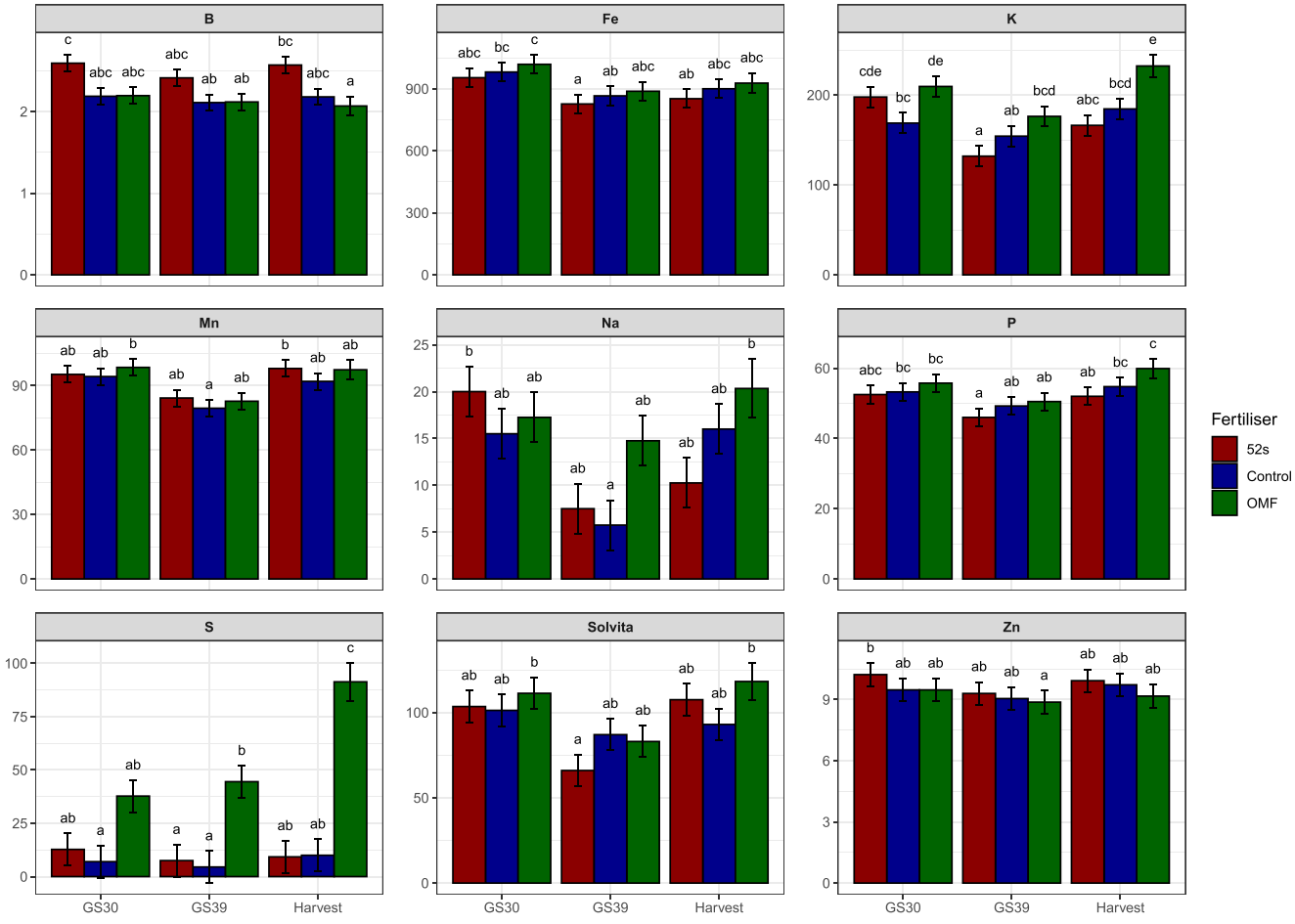


Fig. 1. Soil extractable nutrient concentrations under spring barley at GS30, GS39 and final harvest at Market Weighton. Bars represent estimated marginal means, error bars indicate standard error, and letters indicate statistically significant differences at $p < 0.05$ using Sidak's test. Nutrient concentrations are expressed as mg L^{-1} of soil extract. Solvita values represent soil respiration, expressed as mg CO_2 kg^{-1} soil day^{-1} .

residuals versus fitted values and quantile–quantile (QQ) plots of both residuals and random effects.

3. Results

3.1. Soil and leaf nutrients

In the Market Weighton spring barley crop, OMF caused significant increases in soil S (~80 mg L^{-1} and K (~60 mg L^{-1}) by the harvest time, when compared to mineral fertiliser and the control. The effect of fertiliser on soil nutrient levels was less pronounced in all other assessed nutrients and across all three assessments from early to late growth stages (Fig. 1). Leaf nutrients such as B, Ca, and Mg increased in response to both fertilisers from GS30 to GS39, but no significant effect of fertiliser type was observed for these nutrients. Leaf S levels were the only significant effect of fertiliser type at GS39 with OMF increasing the S levels when compared to the mineral fertiliser. Only levels of soil S and Zn were significantly affected by fertiliser type in the Felixstowe spring barley crop (Table 2). Using only OMF significantly increased soil S levels when compared to mineral fertiliser or combining mineral fertiliser and OMF. Soil Zn levels were significantly lower in the combined OMF and mineral fertiliser treatment than in the control, where no fertilisers of any type were applied. Soil Zn levels were otherwise unaffected by fertiliser type. No soil nutrients were significantly affected by fertiliser type in the Hingham oats crop and leaf nutrients were not assessed for this crop. (Fig. 2).

3.2. Grain quality

In the Market Weighton spring barley crop, grain nutrients showed minimal response to fertiliser type (Table 1). No significant differences were found in P, K, Mg, or S between the 52 s and OMF treatments, while the control plot gave lower S levels. At the Felixstowe site, fertiliser effects on grain nutrients were more pronounced. P levels were higher in the control treatment compared to all fertilised plots, but S was higher in all fertiliser treatments. The control also had lower protein but higher Zn compared to the fertilised plots. At Hingham, the fertiliser treatments had a minimal impact on nutrient concentrations in the oat crop. P and Zn were higher in the control than the fertiliser treatments whilst and S and Zn levels were slightly elevated in the 52 s/AN and OMF/AN treatments compared to the control, but no significant differences were observed in almost all nutrients.

3.3. Crop performance (Market Weighton Spring Barley)

The linear mixed-effects polynomial model indicated that yields with OMF were lower than those with 52 s by 1.45 t ha^{-1} overall ($p < 0.001$) (Table 3). This reduction represents the average effect across all nitrogen application rates, regardless of whether the rate is low or high. The relationship between N rate and yield was non-linear, with significant contributions from both the linear ($p < 0.001$) and quadratic components ($p < 0.001$). However, the interaction between OMF and the quadratic component was significant only in the latter half of the curve ($p = 0.016$), suggesting that the effect of OMF on yield differs from 52 s

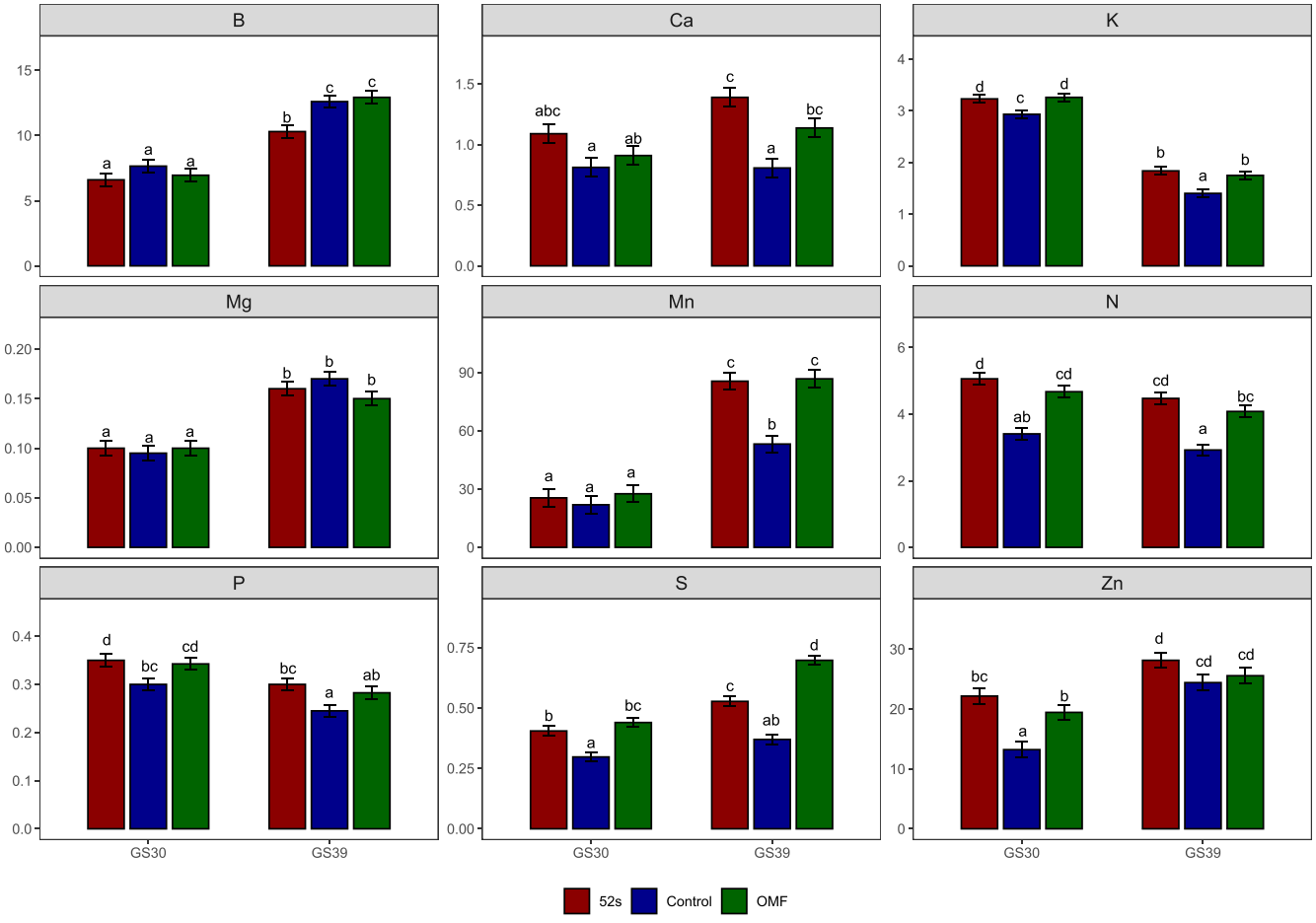


Fig. 2. Leaf nutrient concentrations of spring barley at GS30 and GS39 at Market Weighton. Bars represent estimated marginal means, error bars indicate standard error, and letters indicate statistically significant differences at $p < 0.05$ using Sidak's test. Macronutrients (N, P, K, Ca, Mg and S) are expressed as % dry matter, while micronutrients (B, Mn and Zn) are expressed as ppm.

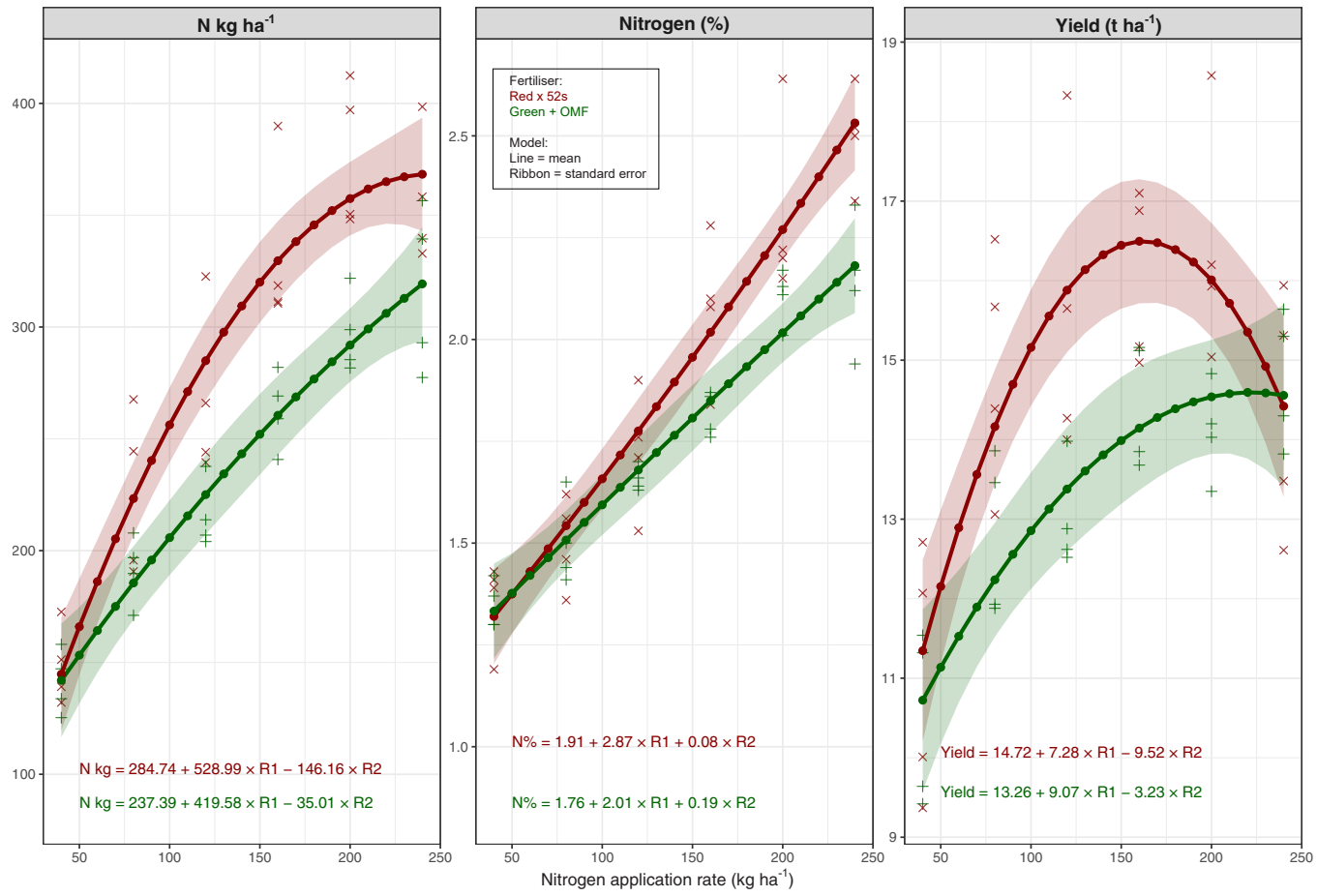


Fig. 3. Effect of fertiliser type and nitrogen application rate on spring barley grain nitrogen concentration (%), nitrogen yield (kg ha^{-1}), and grain yield (t ha^{-1}) at Market Weighton. Fitted equations are shown for each fertiliser type, using orthogonal polynomial components R1 (linear) and R2 (quadratic).

at higher nitrogen rates. The plotted estimated marginal means showed that mineral fertiliser tended to produce higher yields at these higher N application rates (Fig. 3). OMF reduced N percentage by an average of 0.148 units overall across all N rates ($p < 0.001$). The relationship between N rate and N percentage was primarily linear ($p < 0.001$). The significant interaction between OMF and the first polynomial component ($p = 0.002$) suggests that the increase in nitrogen percent with increasing N rate was less pronounced for OMF compared to 52 s. However, this effect was uniform across all application rates, as neither the second polynomial component nor its interaction with OMF were significant ($p = 0.643$ and $p = 0.682$). N yields were 47.35 kg ha^{-1} lower when using OMF across all N rates ($p < 0.001$). The response to nitrogen rate was non-linear, with both linear ($p < 0.001$) and quadratic ($p < 0.001$) terms being significant. The interaction between OMF and the first polynomial component was almost significant ($p = 0.051$), while the interaction with the second component was just significant ($p = 0.048$), indicating that differences in N kg ha^{-1} between fertilisers were more pronounced at higher application rates. This implies that lower rates of OMF application were better at providing crop nutrients than higher application rates. This was also confirmed in the plotted estimated marginal means shown in Fig. 2.

3.4. Crop Performance (Felixstowe Spring Barley)

The linear mixed-effects model for yield indicated that yields following early OMF applications were lower than when only mineral fertiliser was applied, by 0.58 t ha^{-1} ($p = 0.012$). This was a smaller decrease compared to the reduction observed at Market Weighton. The relationship between N rate and yield was non-linear, with both the linear and quadratic components being significant ($p < 0.001$ for both). Although the interactions between OMF and the polynomial terms were not significant ($p = 0.351$ and $p = 0.252$), the estimated marginal means plots reveal a more pronounced separation between fertilisers at higher nitrogen application rates, where 52 s tends to result in higher yields compared to OMF (Fig. 4). N yields were 8.05 kg ha^{-1} lower following early OMF applications overall ($p = 0.012$). The effect of nitrogen rate on N kg ha had significant linear ($p < 0.001$) and quadratic components ($p = 0.002$). Although the interactions between OMF and the polynomial components were not significant ($p = 0.351$ and $p = 0.252$), the estimated marginal means plots illustrate a similar trend to yield, with 52 s generally producing higher values of N kg ha at higher nitrogen application rates (Fig. 4). N percent was lower following OMF by 1.91 units overall ($p > 0.001$). The relationship between nitrogen application rate and N yield was strongly non-linear, with both the linear ($p < 0.001$) and quadratic ($p = 0.002$) components contributing significantly to the model. Although the interaction terms between OMF and the polynomial components were not statistically significant ($p = 0.351$ and $p = 0.252$), the emmeans plots show that the difference between 52 s and OMF becomes more evident at higher nitrogen application rates.

3.5. Crop performance (Hingham Oats)

The linear mixed-effects model for oat yield gave a slightly lower yield of 0.38 t ha^{-1} ($p = 0.021$), with this effect being more pronounced at lower nitrogen application rates, as shown in Fig. 5. Neither the linear nor the quadratic components of nitrogen rate were significant ($p = 0.805$ and $p = 0.491$, respectively), suggesting no strong

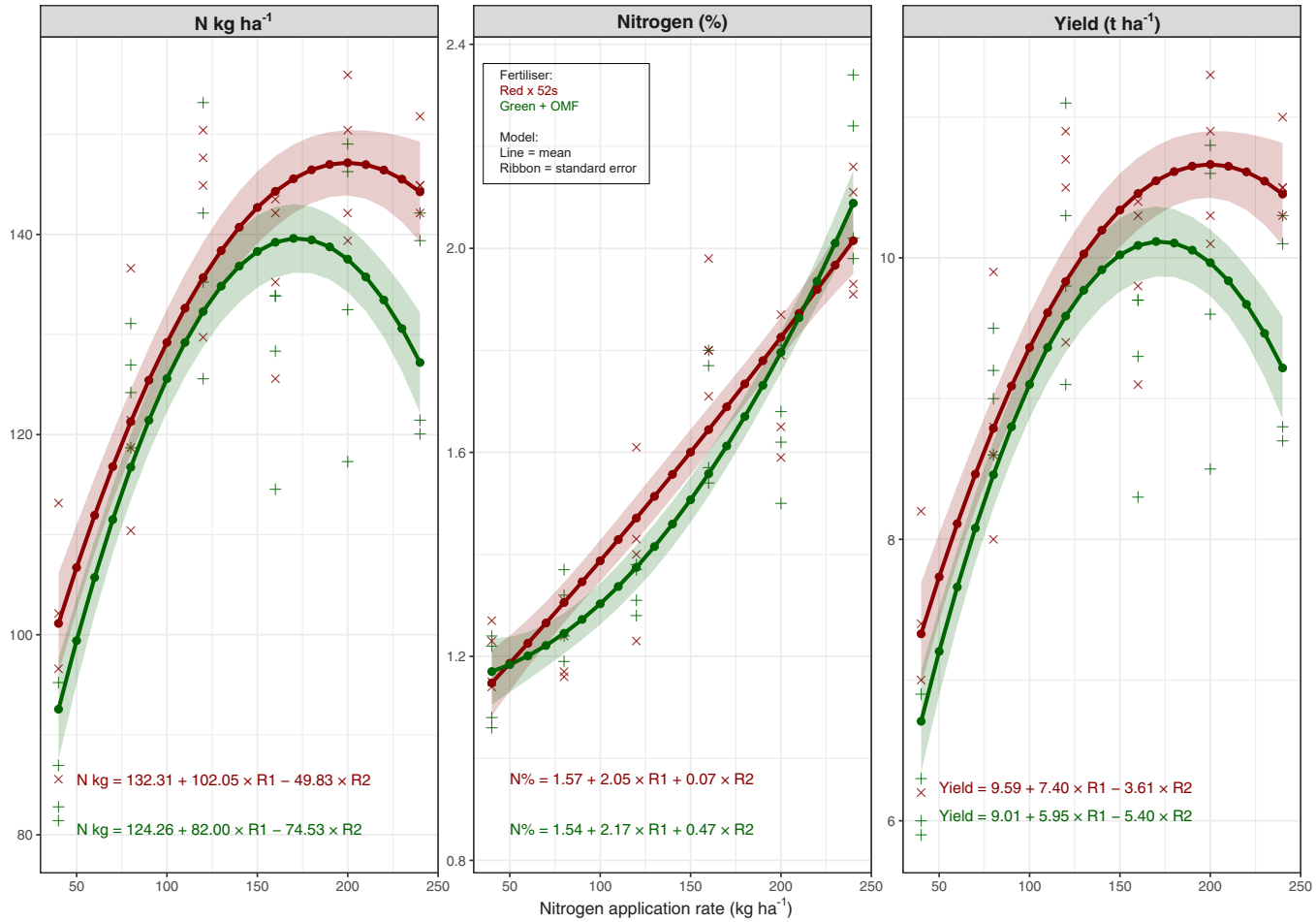


Fig. 4. Effect of fertiliser type and nitrogen application rate on spring barley grain nitrogen concentration (%), nitrogen yield (kg ha^{-1}), and grain yield (t ha^{-1}) at Felixstowe. Fitted equations are shown for each fertiliser type, using orthogonal polynomial components R1 (linear) and R2 (quadratic).

relationship between nitrogen rate and yield in this trial. This indicates that variations in nitrogen application did not meaningfully influence yield for either fertiliser type. The interactions between OMF and the nitrogen rate components were also not statistically significant ($p = 0.108$ and $p = 0.383$), indicating that the yield response to nitrogen rate was similar for both fertilisers across all application rates. OMF significantly reduced N kg ha^{-1} by 5.35 kg ha^{-1} overall ($p = 0.032$). The first polynomial component of nitrogen rate had a significant positive effect ($p = 0.023$), suggesting that N yield increased with nitrogen application in both fertilisers. However, the second component was not significant ($p = 0.366$), indicating no significant curvature in the response. The interactions between OMF and the nitrogen rate components were also non-significant ($p = 0.105$ and $p = 0.346$), implying that the effect of nitrogen rate on N yield did not differ between fertilisers. OMF had no significant effect on N%. The response to nitrogen rate was primarily linear ($p < 0.001$), with no significant contribution from the quadratic component ($p = 0.252$). The interactions between OMF and the nitrogen rate components were not significant ($p = 0.235$ and $p = 0.906$), indicating that N percentage was influenced only by the rate of application, with minimal impact from the fertiliser type.

4. Discussion

The increase in soil S following OMF application when compared to the mineral fertiliser occurred across two of the three sites, where OMF was applied throughout (Market Weighton) and where OMF was only applied in the early growth stage (Felixstowe). This was likely due to the higher S content of the OMF compared to the mineral fertiliser. This enrichment of soil S indicates S immobilization did not take place in these two sites, an effect also observed with S-rich OMFs in other studies (Moharana et al., 2015). OMF at both applications raised soil S in Felixstowe, but the comparatively smaller S application in the OMF at the seedling stage did not. No changes for soil nutrients were observed for any nutrient in the oats crop in Hingham. Given the negligible effect of both fertilisers on the oat crop however, it seems likely that something prevented mineralization of both OMF and mineral fertiliser throughout the growing season, restricting crop growth and resulting in no soil nutrient level changes. We postulate that the soil nutrient levels for Higham were much higher than the other sites (Table SM1), additional nutrient provided by the added treatments did not cause a measurable effect. The weather data indicated rainfall was higher in the early growing period of 2023 in Hingham than in the growing period of Market Weighton, and a little bit higher than Felixstowe (Figure SM1). The light soils in Norfolk can be prone to leaching of nutrients following fertiliser applications in the spring growing period (Davies and Sylvester-Bradley, 1995). This may explain why both fertilisers had such minimal effect in this trial, on grain yield and soil quality. The increase in soil S observed in two sites, and the increase in barley leaf S observed in Market Weighton, indicates that S-enriched OMFs can supply S in cereal systems where S fertilisation is uncommon (Zhao et al., 1995).

Fertiliser type had a limited effect on grain nutrient concentrations at Market Weighton, with no significant differences observed between 52S and OMF treatments and only the control showing lower S levels. The supply of S from both fertilisers increased grain S, and the additional S in the OMF did not further raise grain S despite higher soil S. In contrast, fertiliser effects were more pronounced at Felixstowe, where control

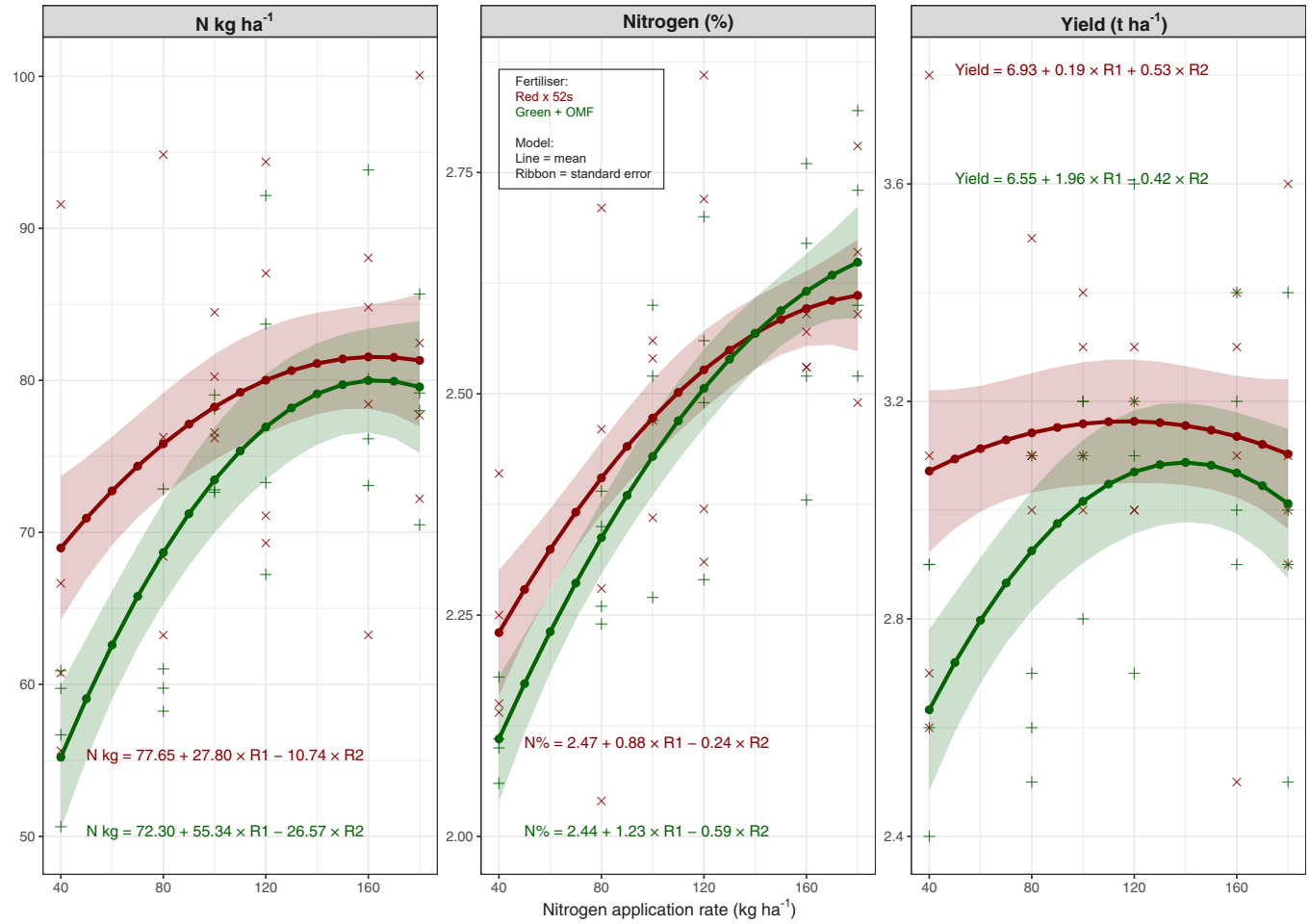


Fig. 5. Effect of fertiliser type and nitrogen application rate on spring oats grain nitrogen concentration (%), nitrogen yield (kg ha^{-1}), and grain yield (t ha^{-1}) at Hingham. Fitted equations are shown for each fertiliser type, using orthogonal polynomial components R1 (linear) and R2 (quadratic).

plots had higher P but lower S, and fertiliser treatments increased grain protein. The higher Zn in the control may reflect reduced Zn availability under elevated P (Ryan et al., 2008). At Hingham, fertiliser treatments had minimal impact on grain nutrients, although slight increases in S and Zn were observed in the 52S/AN and OMF/AN treatments.

Studies comparing the impact of OMF applications to mineral fertiliser applications in winter barley have often the effect of OMF to be comparable to mineral fertiliser when the same N application rate is applied (Burak and Sakrabani, 2023, Deeks et al., 2013, Ferrari et al., 2022). This study however described no effect of fertiliser type at some application rates and a significant minor reduction in other application rates of OMF on spring barley grain and N yield, a finding also found by Smith et al. (2015). This occurred whether only OMF was applied throughout (Market Weighton) or when OMF was applied to seedbed and then followed up later in the season with mineral fertiliser (Felixstowe). This implies the effect of OMF tended to restrict yields when applied at the early growth stages. Spring barley crops will have less-developed root systems than winter barley crops when they receive their initial fertiliser application, and whilst this may restrict nutrient uptake, this restriction did not appear to take place when mineral fertiliser was used. The availability of nutrients from the OMF at this point of growth may then have been the pivotal factor in the slight reductions in grain and N yield observed in these two crops.

The application of C-rich organic materials improves soil health in the long-term, but the potential short-term immobilization of nutrients that this can cause is a perennial issue in arable farming (Chen et al., 2022). It is possible that the C content of the OMF used in these trials caused N immobilization in the early growth stages, but it may also be that the nutrition contained within the OMF was not mineralized quickly enough after application. This is most likely because whilst the OMF trialled had a significant C component, the C was derived from green compost, which is believed to have a low C:N ratio of around 10–20:1 (Sitzmann et al., 2024). Organic materials that cause nutrient immobilization such as cereal straw and paper mill waste etc. typically have C:N ratios that exceed 40:1 (Cheshire et al., 1999, Camberato et al., 2006). The C component of the applied OMF was therefore unlikely to cause significant nutrient immobilization, and this hypothesis is supported by the increase in soil S observed in both sites throughout the growing season. A more likely explanation for the small yield penalties incurred by the OMF is therefore the slower release of nutrients, rather than the immobilization of nutrients within the soil microbiome. This may have been exacerbated by drier conditions at time of application in both trials.

The impact of fertiliser treatments on the oats trial in Hingham was limited. Neither N rate nor fertiliser type significantly affected grain yield. Table SM1 shows that P, K and Mg levels were already well above RB209 targets (AHDB, 2023) likely suppressing any fertiliser response. This inherent fertility, combined with the potential for nutrient leaching on light soils, may explain the absence of treatment effects on both soil and grain nutrient levels.

The effect of OMF applications on grain yield and soil health of two arable sites was comparable to mineral fertiliser at most N application rates. Although the S-rich OMF trialled did significantly increase the soil S levels throughout the trial, the impact of OMF on soil health was more negligible with respect to other soil nutrients. These results highlight nutrient availability of organic amendments following application can be hard to predict and is influenced by the composition of the

amendment (in this case OMF) as well as environmental factors like soil texture, nutrient status, and rainfall. It is known that all organic systems have the potential to incur yield penalties, but here we show that this can also be the case when conventional and organic materials are blended. OMF can be produced from a range of organic and inorganic materials. The spectrum of C/nutrient content as well as the lability of the C will influence nutrient availability. OMF may then be most optimally used when expected nutrient availability best synchronises with the desired crop. This study showed that despite OMF having a lower nutrient content compared to mineral fertiliser, carbon lability of the organic component of its formulation can mineralise nutrients when used in conjunction with mineral fertilisers. Quality of organic feedstock within OMF is vital to integrate its application with mineral fertiliser so a more circular economy approach to meet food security whilst ensuring sustainable soil health management is implemented.

This study has some limitations that should be considered when interpreting the results. Although experiments were carried out at three sites, each site was assessed over a single season, and fertiliser responses may vary under different weather conditions or in different rotations. Only one OMF formulation was evaluated, so the findings may not apply to OMFs produced from other materials. Although soil sampling was carried out throughout the growing season, the soil microbiome was not studied, meaning inferences about nutrient mineralisation and immobilisation were only speculative. Site-specific conditions, particularly the high baseline fertility at Hingham and the restricted soil and grain nutrient assessments at only one N rate per fertiliser, may also limit the general applicability of the results from this site.

5. Conclusions

This research provides a synopsis of three one-year studies to evaluate potential to integrate OMF as part of sustainable fertiliser management concurrent with mineral fertiliser applications in three locations in England. It showed that the organic feedstock used as part of the OMF formulation is key in determining nutrient availability to meet crop nutrient demands. The crop yield response and quality are site and crop specific. For the spring barley, the yield responses showed that OMF application, whether used alone or combined with mineral fertiliser, led to small reductions in grain and nitrogen yield at the higher application rates. However, for the spring oats as the soil was very fertile, yield responses were not apparent.

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CRediT authorship contribution statement

Patrick McKenna: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis. **Emma Burak:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James A. Harris:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ruben Sakrabani:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used [Chat GPT] in order to [assist in R coding to complete our statistical analysis and produce plots]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128060.

Data availability

Data supporting this study are openly available from CORD at DOI: https://doi.org/10.57996/cran.ceres-2827

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Evaluating efficacy of organo-mineral fertiliser to meet nutrient demands of cereal crops in England

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