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Effect of Polymer-Coated Urea/Urea Blends on Corn Yields under Short Growing Season Conditions in Eastern Canada

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Abstract: Polymer-coated urea (PCU) was developed to better synchronize nitrogen (N) supply with crop needs and reduce N losses. The objective of this work was to evaluate the effects of different N rates prepared using combinations of urea and ESN (PCU) on corn (*Zea mays* L.), grain yield, yield components, in-season nutritional status, and residual soil N. Field experiments were conducted on two sites in eastern Ontario (Canada); Kemptville (sandy loam) and Winchester (clay-loam), and repeated over three years (2011–2013). A total of ten treatments were applied using combinations of three N rates (50, 100, and 150 kg N ha^{-1}) and three fertilizer proportions (100% urea, 75:25 urea:ESN, and 60:40 urea:ESN) for each rate. The tenth treatment consisted of a non-fertilized control (0 N). Grain yield was significantly affected by N source, N rate, site, and year. There was no significant effect of the N source in most sites/years. In the wetter season 2013, treatment 100N60:40 in the sandy site produced a similar yield to treatments receiving 150 kg N ha^{-1}. In the clay-loam site, the 150N75:25 treatment had a yield advantage of 11–12% compared with straight urea. Chlorophyll index generally increased with the higher N application rate. The other grain parameters were little affected by the N rate or source. Soil residual mineral N tended to increase with ESN blends at 100 and 150 kg N ha^{-1} compared with straight urea. Our findings indicate that replacing a portion of urea with PCU might save N in lighter soils prone to leaching especially in wet years without affecting yields.

Keywords: maize; polymer-coated urea; slow-release fertilizer; chlorophyll content; environmental conditions; soil texture; nitrogen solubility; nitrogen losses

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1. Introduction

Nitrogen (N) availability to crops and losses to the environment have always been an issue when deciding when, how, and how much N should be applied. Polymer-coated urea (PCU) fertilizers have urea granules coated with a thin polymer designed to slow N release into the soil. This technology aims at matching the timing of N availability with crop demand; therefore, reducing N losses to the environment and increasing N use efficiency [1]. In warm and wet conditions in Illinois, PCU releases lower N_2O emissions compared with urea or anhydrous ammonia [2]. Recent research from Brazil shows that PCU significantly cuts ammonia volatilization losses compared with other N fertilizers applied as top-dressing, especially in sandy soils [3]. Research reports on the yield effects of using PCU instead of regular non-coated urea have been mixed. Research findings have suggested that the effect from PCU depends on coating thickness [4], temperature [5], soil type [5–7], soil moisture [1,8,9], organic matter content [1], and application method [9,10]. A report from Iowa (USA) showed that ESN, among other enhanced-efficiency fertilizers, consistently increased yields in continuous corn [11]. Research in China has shown the possibility of obtaining the same corn yield with 70% of the fertilizer amount when using PCU instead of urea at an application rate of 240 kg N ha^{-1} [12]. In wheat (*Triticum aestivum* L.), some researchers have observed that PCU resulted in higher grain yield, dry matter production, and nutrient uptake efficiency [13–15]. In Missouri corn (*Zea mays* L.) trials, Noellsch et al. [16] reported a yield advantage associated with using PCU as opposed to urea in low-lying landscape positions, but there was no difference in summit or sideslope positions. Similarly, in Brazil the use of different N fertilizer sources including PCU did not change corn yield compared with the untreated control [3]. Analyzing several research reports from north-central United States, Nelson et al. [7] reported that pre-plant applications of PCU had median corn grain yields greater than urea or urea ammonium nitrate. They concluded that poorly drained soils subject to denitrification and soils with leaching potential may benefit greatest from PCU. The increase in grain yield may be also due to reduced weed competition for soil N when ESN is used [14]. In addition, the slower N release from PCU can result in a higher grain protein concentration [17–20]. On the other hand, other reports have suggested that PCU decreased crop yield when applied to planting in drier years compared with urea [21]. A study encompassing 15 site/years of field trials across Canada on multiple crops concluded that uncoated urea was at least as effective as PCU in terms of crop yield, grain N concentration, total N accumulation at harvest, and N use efficiency compared with standard regional timing and placement of non-coated urea [1]. When PCU reduced yield (and dry matter), the reduction was attributed to delays in release of N from the granule that limited early season N availability and crop growth, especially in corn, which has a high N demand [1]. In addition to the contrasting reports, utilizing different ratios of urea and ESN to overcome some of these challenges is rare in the literature. The objective of this study was to evaluate the effect of different combinations and rates of ESN and urea on corn yield and grain characteristics under two contrasting soil textures under short growing season conditions in eastern Canada. We hypothesized that ESN blends would increase corn yields compared with straight urea.

2. Materials and Methods

2.1. Site Description and Experimental Layout

This experiment was conducted at the University of Guelph Kemptville (latitude 45.01 N, longitude 75.63 W, elevation 99.4 m) and Winchester (lat. 45 06 N, long. 75 34 W) Research Stations in eastern Ontario, Canada. According to the Canadian soil classification, the soil in the Kemptville site is a Grenville sandy loam belonging to the Eutric Brunisolic great soil group (equivalent to Eutrochrepts soil great group according to the USDA soil classification) with good drainage [22]. The soil in the Winchester site is an imperfectly drained North Gower clay loam (Typic Endoaquolls) belonging to the Orthic Humic Gleysol subgroup.

The factors studied were N rates (50, 100, and 150 kg N ha^{-1}) and N source blends (100% urea, 75:25 urea:ESN, and 60:40 urea:ESN). Nine treatments resulted from the combination of the rates from these two factors in addition to a tenth treatment that did not receive any N (control). Treatment names used here indicate the rate and blend ratio (e.g., 50N60:40 indicates a rate at 50 kg N ha^{-1} using a 60:40 urea:ESN blend). A 100% ESN treatment was not tested due to multiple previous reports showing that replacing urea or similar products with 100% ESN did not increase corn yields, e.g., [23,24]. The experiment was repeated on two different sites and three years (2011–2013) resulting in six site/years. Therefore, site and year were also considered independent factors in the statistical analysis.

For rotation purposes, the ranges used for the experiment changed from year to year. Previous crop, field preparation, soil properties, and other crop management information is presented in Table 1. The experiment was laid out according to a randomized complete block design with four replications. The size of the plot was 3 m × 6 m with a row width of 76 cm and an in-row spacing of ~16 cm. Fertilizers were broadcast and incorporated into the topsoil using a cultivator before planting. NK RoundUp Ready corn hybrids adapted for the local climate were selected (Table 1). The seeds were planted with a John Deere 7000 four-row planter at ~8.6 seeds m^{-2}. Weather conditions were recorded by an

Environment Canada weather station at the Kemptville Research Station. The long-term average is based on data from 1971 to 2000 [24].

2.2. Soil Sampling and Analysis

Composite samples were taken from the topsoil (0–15 cm) just before seeding to determine initial soil physical and chemical properties. The samples were air-dried overnight and then oven-dried at 50 °C for 24 h and stored at room temperature until analysis. Organic matter content was determined by loss on ignition method (at 350 °C). The concentration of organic C and total N was determined using a CNS analyzer (VarioMAX cube, Elementar Analysensysteme GmbH, Hanau, Germany) after carbonate removal. Exchangeable phosphorus was determined using the Olsen sodium bicarbonate method [25]. Exchangeable potassium was determined using the ammonium acetate extraction method [26].

Another set of soil samples were taken at 30 cm depth in each plot shortly after harvest to estimate residual mineral N (RN_{min}) concentrations (ammonium + nitrate). Samples were frozen immediately at −15 °C until analysis. Soil mineral N was extracted from thawed soil with 2 mol L^{-1} KCl (1:5 soil to extractant ratio), and the NO_3-N and ammonium-N (NH_4-N) fractions were determined by colorimetry using the modified indophenol blue technique [27] with an Epoch microplate spectrophotometer (BioTek Instruments Inc., Winooski, VT, USA).

Table 1. Selected management information and soil chemical properties for the different sites and years.

	Kemptville			Winchester		
	2011	**2012**	**2013**	**2011**	**2012**	**2013**
Previous crop (all finished in the previous fall before planting)	Switchgrass (*Panicum virgatum* L.)	Red clover (*Trifolium pratense* L.) and timothy (*Phleum pratense* L.) (2010–2011)	Reed canarygrass (*Phalaris arundinacea* L.) and cereals	Wheat	Wheat	Soybean (*Glycine max* (L.) Merr.)
Fall tillage	Offset disc	Chisel plow	Moldboard	Chisel Plow	Moldboard	Moldboard
Spring tillage (with number of passes)	Disc, Cultivator	Disc, Cultivator	Disc, Cultivator (2)	Disc, Cultivator	Cultivator (2)	Cultivator (2)
Planting date	13-May	20-Apr.	6-May	25-May	7-May	10-May
Harvest date	25-Nov.	25-Oct.	21-Nov.	17-Nov.	26-Oct.	20-Nov.
Other fertilizer application			80 kg K_2O ha^{-1}			50 kg P_2O_5 ha^{-1}, 30 K_2O kg ha^{-1}
Maize hybrid	N23F-3000GT	N23F-3000GT	N20Y-3000GT	N23F-3000GT	N23F-3000GT	N20Y-3000GT
Organic matter (g kg^{-1})	31	36	29	28	26	28
pH	6.10	6.50	6.55	6.57	7.70	6.34
P concentration (mg kg^{-1}) and level according to OMAFRA *	39 (RR)	41 (RR)	42 (RR)	27 (LR)	30 (LR)	11 (MR)
K concentration (mg kg^{-1}) and level according to OMAFRA *	83 (MR)	90 (MR)	63 (MR)	134 (LR)	193 (RR)	113 (MR)
NO_3 concentration (mg kg^{-1})			8.3			16.5
NH_4 concentration (mg kg^{-1})			1.50			4.00

*: Yield response rating to additional fertilizer application according to the Ontario Ministry of Food, Agriculture, and Rural Affairs [28]. LR: low response; MR: medium response; RR: rare response.

2.3. Parameters Monitored and Sampling Procedures

Indirect determination of leaf chlorophyll content (or chlorophyll index) was performed using SPAD-502Plus (Konica-Minolta, Osaka City, Japan) chlorophyll meter, which measures light absorbance by a section of the leaf. Readings were taken at different development stages during the growing season starting at vegetative stage tasseling (VT) (in mid-July), although readings were not always taken at the same stages across years and sites. For each plot, leaf chlorophyll index readings were made on eight–eleven random plants from the two middle rows, taken on the last fully expanded leaf until ear initiation and then the ear leaf was measured for the remainder of the growing season. Readings were collected from one side of the mid-rib at the maximum width of the leaf. The readings were averaged to obtain one mean value for each plot at each date.

After a killing frost, the central two rows in each plot were harvested using a Hege 140 plot combine (HU Hege, Hohebuch, Germany). Grain moisture content, grain yield (adjusted to 155 g kg^{-1} moisture content), thousand kernel weight, and grain test weight were determined at harvest. Thousand kernel weight was determined by weighing a 200-grain random sample from each plot. Test weight was determined by filling a 0.5 L beaker with grains and weighing the grains [29]. Moisture content was determined after oven drying at 105 °C until constant weight is achieved [29].

2.4. Statistical Analysis

All data collected were subjected to analysis of variance using the Proc Mixed model in SAS [30]. Differences were considered significant at $p \leq 0.05$ for all analyses. Statistical analysis showed significant effects of year and site, and significant interaction between these two factors on most parameters. Therefore, we decided to analyze each year and site results separately. Within a year and a site, fixed effects were N rate, N source, and N rate x N source interaction, while block was a random effect. The means were separated using Tukey's HSD test when the F-test was significant. For a consistent and easier presentation of results, letters were used to separate means when at least one factor was significant, whether the interaction was significant or not. Moisture content percentage data were arcsine transformed before analysis to ensure a normal distribution [31].

3. Results and Discussion

3.1. Weather Conditions

Average year temperatures between 2011 and 2013 were higher than their respective long-term averages (Table 2). On the other hand, precipitation during the growing season (May to September, inclusive) for the same period was below the long-term average, with 267, 258, and 417 mm for 2011, 2012, and 2013, respectively. July and August 2012 were particularly dry with 34.3 and 16.8 mm, respectively.

Table 2. Precipitation and temperature recorded at the Kemptville experimental site between 2011 and 2013 in addition to long-term (30 year) averages.

	Precipitation (mm)				Temperature High (°C)				Temperature Low (°C)			
	30-yr Average	2011	2012	2013	30-yr Average	2011	2012	2013	30-yr Average	2011	2012	2013
Jan.	63.8	18.1	63.7	60.8	−5.3	−6.4	−2.7	−2.8	−15.2	−14.6	−13.5	−13.8
Feb.	61.1	45	21.3	59.6	−3.7	−2	0.7	−2.9	−13.9	−13	−9.3	−11.7
Mar.	70	95.4	38.6	19.0	2.5	2.8	10	3.0	−7.5	−6.7	−2.4	−6.0
Apr.	80.5	140.8	55.7	47.8	10.8	12.1	11.5	11.4	0.4	0.6	0.4	−0.1
May	83.8	71.2	73.7	78.4	18.6	19	22	21.2	6.8	8.3	8.7	7.5
Jun.	77.9	32	62.3	122	23.6	24.7	25.2	22.2	11.9	13.1	12.6	12.2
Jul.	97.5	35.8	34.3	61	26.4	28.7	29.7	27.9	14.4	15.5	15	15.9
Aug.	84.1	95.9	16.8	78.7	24.9	26.3	26.8	24.7	13.2	13.8	13.8	13.4
Sep.	92.8	32	70.6	76.8	19.6	22.8	21.1	20	8.5	10.5	8.3	7.9
Oct.	81.8	80.4	4.8	50.2	12.7	14.4	15.3	16	2.8	4.6	4.9	4.6
Nov.	83.7	60.7	46.2	53.6	5.2	10	5.6	4.8	−2.7	0.5	−4.6	−5.2
Dec.	84.7	56.7	141.3	71.1	−2.1	0.5	−0.7	−4.3	−11	−8.2	−8.5	−12.7
Precipitation total/temperature average	962	764	629.3	779	11.1	12.7	13.7	11.8	0.642	2.03	2.12	1.00
Growing season (May–September)	436	267	258	417	22.6	24.3	25.0	23.2	11.0	12.2	11.7	11.4

3.2. Leaf Chlorophyll Index

Leaf chlorophyll index, indirectly representing chlorophyll content, was significantly affected by the four main factors: year, site, rate, and source (Table 3). Some of the interactions were also significant. This value was higher in 2012 than the other two years (Table 4). This parameter was consistently lower in the unfertilized control treatment compared with fertilized treatments (Supplementary Table S1). In general, chlorophyll index values were higher with the 150 kg N ha^{-1} fertilizer rate most of the dates. They were also higher for urea compared with ESN blends earlier in the season (VT). After the VT stage, leaf chlorophyll index tended to be greater with the smaller PCU fraction (75:25) than the other treatments. On the other hand, chlorophyll index values tended to decrease with the 60:40 blends compared with the other two blends.

Table 3. Model components and probability values for factor main effects (nitrogen (N) source, N rate, year, and site) on studied parameters, and two-, three- and four-way interactions (n = 4).

	Thousand Kernel Weight	Test Weight	Yield	Moisture Content	Chlorophyll Index (VT *)	Chlorophyll Index (R1 Silking)	Soil Mineral Nitrogen
Component				P > F			
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site	<0.0001	<0.0001	0.0301	<0.0001	<0.0001	<0.0001	<0.0001
Nitrogen Source	0.3067	0.0031	<0.0001	0.0132	<0.0001	<0.0001	0.0002
Nitrogen Rate	0.4893	0.0396	<0.0001	0.0908	<0.0001	<0.0001	<0.0001
Block	0.3845	0.9500	0.0322	0.0004	0.1907	0.3092	0.6507
Year × Site	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year × Source	0.5614	0.0392	0.209	0.0044	0.3278	0.592	0.0195
Year × Rate	0.4974	0.9388	0.058	0.0033	0.1767	0.0823	<0.0001
Site × Source	0.6699	0.4038	0.1886	0.1924	<0.0001	0.2099	0.896
Site × Rate	0.0416	0.0085	0.2928	0.0255	<0.0001	0.0036	0.6639
Source × Rate	0.2783	0.4653	0.9771	0.8253	0.5041	0.5551	0.0357
Year × Site × Source	0.5955	0.5222	0.1302	0.9548	0.6995	0.005	0.5569
Year × Site × Rate	0.1613	0.5081	0.375	0.6097	0.6234	0.0045	0.0721
Site × Source × Rate	0.3124	0.0273	0.8271	0.148	0.9875	0.9842	0.594
Year × Site × Source × Rate	0.5166	0.2475	0.7217	0.6254	0.9081	0.4354	0.4531

* VT: vegetative stage tassel; R1: silking stage.

Table 4. Effect of year, site, nitrogen (N) source, and N rate, on leaf chlorophyll index in corn plants. Readings at stages R5 Dent and R6 Maturity were taken only in 2013, and not in previous years.

		Leaf Chlorophyll Index			
Factor		**VT**	**R1 Silking**	**R5 Dent**	**R6 Maturity**
Year					
	2011	33.6 c	42.2 b		
	2012	48.3 a	49.7 a		
	2013	34.9 b	32.8 c		
Site					
	Kemptville	36.3 b	42.9 a	29.9 b	21.2 a
	Winchester	42.0 a	40.3 b	33.0 a	22.8 a
N Source					
	No fertilizer	34.9 c	33.4 c	25.1 b	18.0 b
	Urea	40.8 a	42.5 ab	31.3 a	22.6 a
	75:25 Urea:ESN	39.9 ab	43.5 a	33.4 a	23.2 a
	60:40 Urea:ESN	39.1 b	41.4 b	31.7 a	21.6 a

Table 4. *Cont.*

Factor		Leaf Chlorophyll Index VT	R1 Silking	R5 Dent	R6 Maturity
N Rate					
	0	34.9 c	33.4 d	25.1 c	18.0 c
	50	38.0 b	39.1 c	29.6 b	20.3 bc
	100	39.0 b	43.1 b	30.1 b	21.9 b
	150	42.8 a	45.2 a	36.8 a	25.1 a

Note: Within a column, values followed by the same letter are not statistically different at $p \leq 0.05$ (n = 4). VT: vegetative stage tassel; R1–R6: reproductive stages.

3.3. Grain Yield

Grain yield was significantly affected by N source, N rate, site, and year. The year–site interaction was also significant (Table 3). Therefore, the effects of N source and N rate were evaluated separately for each year and site.

In Kemptville, a subsoil hard pan compromised yields across treatments in 2011, and resulted in no significant effect of N rate or N source (Supplementary Table S2). In 2012, there was no significant treatment effect, most likely due to contribution of N mineralization from the previous red clover crop. The highest advantage of using blends compared with straight urea was observed in the wettest 2013 season. It is also important to note that treatment 100N100:0 produced the same yield as all treatments receiving 50 kg N ha^{-1}. Treatment 100N60:40 boosted the yield to be at par with treatments receiving 150 kg N ha^{-1}, indicating the possibility for saving 50 kg N ha^{-1} under wet conditions in light soils.

For the clay-loam Winchester site, yields were not statistically different within a N rate. However, an insignificant yield increase was observed with 75:25 blends at 100 and 150 kg N ha^{-1} levels in 2011 and 2013. At 150 kg N ha^{-1} the yield advantage for the 75:25 blend over straight urea was 12% and 14% in 2011 and 2013, respectively (Supplementary Table S2). In 2012 (drier year), blend treatments resulted in lower corn yields in Winchester, especially the 60:40 treatments. For example, the 150N60:40 was 25% lower than the 150N100:0 (6716 versus 8923 kg ha^{-1}, respectively).

3.4. Grain Properties

When analyzing all data for years and sites, the thousand kernel weight was affected by the year and the site factors (Table 3). This parameter was significantly lower in 2013 than the other two years. It was higher in the sandy soil (Kemptville) than the clay-loam soil (Winchester). However, although not statistically significant, thousand kernel weight tended to increase with higher fertilizer rates (Table 5).

Table 5. Effect of year, site, nitrogen (N) source, and N rate, on yield and grain parameters of corn.

Factor		Yield (kg ha^{-1})	Test Weight (kg hl^{-1})	Thousand Kernel Weight (g)	Grain Moisture Content (Arcsined)	Soil Mineral Nitrogen (mg kg^{-1})
Year						
	2011	7724.5 b	73.3 b	333.1 a	0.440 b	10.7 b
	2012	9873.4 a	75.0 a	338.0 a	0.436 c	20.3 a
	2013	10,170.3 a	69.6 c	303.5 b	0.452 a	7.3 c
Site						
	Kemptville	9483.6 a	73.0 a	338.1 a	0.440 b	12.6 b
	Winchester	9018.2 b	72.3 b	311.6 b	0.445 a	14.5 a
N Source						
	No fertilizer	6974.1 b	71.8 b	320.1 a	0.446 a	10.5 b
	Urea	9449.3 a	72.7 a	322.1 a	0.443 ab	13.1 ab

Table 5. *Cont.*

Factor		Yield (kg ha^{-1})	Test Weight (kg hl^{-1})	Thousand Kernel Weight (g)	Grain Moisture Content (Arcsined)	Soil Mineral Nitrogen (mg kg^{-1})
	75:25 Urea:ESN	9736.7 a	72.8 a	329.3 a	0.441 b	13.9 a
	60:40 Urea:ESN	9329.4 a	72.7 a	324.5 a	0.442 b	14.5 a
N Rate						
	0	6974.1 c	71.8 b	320.1 a	0.446 a	10.5 b
	50	8690.5 b	72.6 a	321.8 a	0.443 ab	10.5 b
	100	9610.9 a	72.6 a	327.2 a	0.442 b	13.3 b
	150	10,228.7 a	73.0 a	326.9 a	0.441 b	18.1 a

Note: Within a column, values followed by the same letter are not statistically different at $p \leq 0.05$ (n = 4).

Grain test weight was significantly affected by N rate, year, and site (Table 3). Test weights were higher with fertilizer application than the unfertilized control (Table 5). Test weight was highest in 2012 and lowest in 2013. Test weight was significantly higher in Winchester than in Kemptville.

Grain moisture content at harvest was not clearly affected by any of the studied factors. However, in 2012 in the Kemptville site it was considerably higher than all other site/years due to early harvest dictated by weather conditions.

3.5. Post-Harvest Residual Soil Mineral Nitrogen

The amount of RN_{min} was significantly affected by the N rate, site, and year, but not by the N source (Table 3). RN_{min} tended to increase with the increase in ESN ratio (Table 5). This was mostly true during the dry year 2012 (Table 6). The two-way interactions between the site and the three other factors were also significant (Table 3). In 2011 and 2013, Winchester soil had higher RN_{min} compared with Kemptville (Table 6). The average across all treatments in Winchester was 21.2, 18.8, and 11.6 mg kg^{-1} for 2011, 2012, and 2013, respectively, compared with 10.0, 21.7 and 7.4 mg kg^{-1} for Kemptville for the same years, respectively. More mineral N was left in the ground in the drier year 2012, compared with the other two years, especially in Kemptville.

Table 6. Total mineral nitrogen (N) in soils sampled after harvest as affected by N rate and source at the two experimental sites.

	Mineral Nitrogen Concentration (mg kg^{-1})					
		Kemptville			Winchester	
Treatment	2011	2012	2013	2011	2012	2013
Control (0N)	8.1 c *	14.5 e	7.3 ab	16.7 bc	13.5 d	11.7 a
50N100:0	8.9 bc	16.8 cde	7.7 ab	16.9 bc	15.3 d	11.4 a
50N75:25	8.1 c	16.1 de	6.9 ab	13.6 c	15.0 d	11.3 a
50N60:40	9.0 bc	15.0 e	8.1 a	21.3 abc	16.9 dc	11.7 a
100N100:0	9.6 bc	21.8 bcde	7.3 ab	20.8 abc	18.4 bcd	12.1 a
100N75:25	11.9 ab	24.7 bc	7.4 ab	27.3 ab	18.1 bcd	11.4 a
100N60:40	10.4 bc	24.5 bcd	7.7 ab	21.2 abc	16.7 dc	11.7 a
150N100:0	8.9 bc	22.3 bcde	6.5 b	19.4 abc	23.9 ab	11.2 a
150N75:25	11.1 abc	33.7 a	7.9 ab	24.8 abc	26.7 a	11.8 a
150N60:40	13.8 a	27.6 ab	7.6 ab	30.3 a	23.4 abc	11.8 a

*: Within a column, values followed by the same letter are not statistically different at $p \leq 0.05$ (n = 4).

As for the N source and N rate, urea usually resulted in lower RN_{min}. In 2011, treatment 150N60:40 had the highest amount of RN_{min} in both sites. In the wetter 2013, the differences among treatments were slight in Kemptville while there was no significant effect in Winchester.

4. Discussion

The leaf chlorophyll index was significantly higher in 2012 than the other two years, likely due to lower N losses during this drier year, resulting in higher leaf N and chlorophyll concentrations [32]. In addition, the Kemptville site might have benefited from mineralization of N left by the previous forage mixture consisting of red clover and timothy, and witnessed by the high levels of RN_{min} left after harvest across treatments. Leaf chlorophyll index was generally higher in the crops grown in the heavier soil (Winchester). It is generally recognized that crops respond better to N application in finer soils compared with coarser soils [33].

The leaf chlorophyll index generally increased with higher N application rates. Rashid et al. [34] reported a linear relationship between leaf chlorophyll index at the 5–6 leaf stage and soil nitrate concentration. Maharjan et al. [32] observed a linear increase in this parameter with the PCU treatment up to 168 kg N ha^{-1}; with a relatively smaller or negative effect at higher rates. After the VT stage, the leaf chlorophyll index tended to be greater with the smaller PCU fraction (75:25) than the other treatments. Maharjan et al. [32] reported a general trend of greater relative SPAD readings with the PCU treatment than with urea-ammonium nitrate at most N rates in all growth stages. These findings confirm earlier conclusions that a SPAD meter is a useful tool for direct relative comparison of leaf N status at a specific point in time [35] and to determine the need for fertilizer applications [36].

Our results indicate that the year factor had a significant effect on yields, which in our case can be mostly attributed to rainfall differences in addition to conditions specific to the Kemptville site: plow pan in 2011 and high N mineralization from previous red clover/timothy cover crop in 2012. A report from 87 N response experiments in Pennsylvania (USA) has shown that sites with nitrates levels higher than 21 mg kg^{-1} 4–5 weeks after emergence were non-responsive to N fertilizers [37]. Although mid-season nitrate samples were not taken in our study, RN_{min} levels were higher than this value in six out of the 10 treatments, suggesting how high the N level was earlier in the season before most of the crop uptake took place. Rainfall during the growing season was highest in 2013 (417 mm) compared with 2011 (267 mm) and 2012 (258 mm). Research from a nearby site (within 50 km) reported that N fertilization did not affect yields in a dry year [36]. Similarly, meta-analysis studies have shown that corn yield responses to N increased with higher and well-distributed rainfall [33,38].

Yield generally increased with higher N application rates. However, mean comparison indicates little incremental increase from one level to the next, with the highest yields generally achieved with the 150N treatments, albeit not always statistically higher than the 100N treatments. This finding confirms research from neighboring Ottawa (Canada) reporting that N applications exceeding 120 kg N ha^{-1} in this environment do not translate into higher yields [36].

The spread between the highest and lowest yield values for positive fertilizer treatments was higher in Winchester (4765 kg ha^{-1}) than Kemptville (2772 kg ha^{-1}), which confirms results of Tremblay et al. [33] who showed higher response to N application in fine-textured soils. In both sites in 2013, the highest yield was observed with treatment 150N75:25, although all 150N treatments (and 100N60:40 in Kemptville) were statistically comparable with this treatment. In Kemptville, all treatments receiving 50 kg N ha^{-1} produced the same yield as treatments 100N100:0 and 100N75:25, suggesting that all these treatments had similar amounts of N available to them, possibly due to N losses early in the season with the wet month of June (122 mm of rain). Research comparing different enhanced efficiency urea fertilizers in Missouri has shown that soil nitrate concentration in the untreated urea treatment was much higher (double or triple depending on the season) than ESN at 8 days after fertilization but sharply and quickly decreased with time and was much lower than that of ESN at 46 days after fertilization [39]. Supplying nitrate during the rapid growth stage (late June–early July in the US corn Belt and Canada) is of primordial importance for yields. Recent research across 49 site/years in the US Midwest showed that

45 kg N ha^{-1} may be all that is needed at planting in most cropping scenarios and that sites with coarse texture can benefit from a side-dress application around the V9 stage if rainfall is expected [40].

Comparing yield values from 18 urea:ESN combinations for each level (3 urea:ESN combinations × 3 years × 2 sites) shows that urea:ESN blends never produced lower yields compared with straight urea and produced significantly higher yields than straight urea in one case only; 100N60:40 treatment in Kemptville (sandy soil) in 2013. That same treatment also produced an equivalent yield to all 150 kg N ha^{-1} treatments, suggesting the possibility for saving 50 kg N ha^{-1} under wet conditions in lighter soils.

In an experiment comparing the effect of ESN to urea ammonium nitrate and NutriSphere on corn in North Carolina (USA), Cahill et al. [23] concluded that over five site/years (out of six) no agronomic advantage of ESN over UAN for grain production was demonstrated. In Quebec (Canada) large corn yield increases by PCU in comparison with urea were detected in wetter years with no yield difference in drier growing seasons [41] or seasons with high rainfall and/or low cumulative heat units [42]. A recent meta-analysis based on 866 global observations of 120 studies indicated that application of CRU instead of urea (same N rate) increased corn yield on average by 5.3%. Albeit small, this higher yield can be attributed to lower N losses during the growing season and better synchronization of ESN-N release with crop needs due to the slow release of ESN. This hypothesis is supported by the higher soil RN_{min} left behind the crop with ESN blends, which is in line with previous findings. For example, corn research in Missouri shows that RN_{min} was lower in the ESN treatment than the urea treatment early in the season but the situation was the opposite 90 days after fertilization [39]. Our results also confirm findings by Gagnon et al. [41] who showed that PCU application at 150 kg N ha^{-1} consistently (across three years) increased residual soil NO_3-N compared with the same rate from urea. Lower losses in PCU compared with urea were also reported by Zhang et al. [43] showing lower nitrous oxide emissions, nitrate leaching, and ammonia volatilization by 23.8%, 27.1%, and 39.4%, respectively. A similar finding was reported using ESN (and other controlled-release fertilizers) compared with urea applied to corn in Missouri (USA) [39].

Thousand kernel weight tended to increase with higher fertilizer rates although this effect was not significant. Literature reports show a positive response of this parameter to N applications up to 150 kg ha^{-1} [44]. However, the source of fertilizer did not affect this parameter in our study, which agrees with literature reports comparing urea and PCU [45].

The site affected the grain test weight due to different textures, with the sandy soil presenting a significantly higher test weight. This agrees with results showing that a site with sandy podzolic soil in eastern Canada produced higher corn test weights than loamy or clay soils [44], possibly due to their ability to supply more N.

Nitrogen fertilizer application increased grain test weights compared with the unfertilized control. This agrees with research in eastern Canada showing that test weight increases with higher N application rate [44].

5. Conclusions

Our results show that ESN does not consistently provide an advantage over straight urea. Out of 18 comparisons (nine positive fertilizer treatments by two sites), only one ESN case (100N60:40) provided a statistically higher yield than straight urea (100N100:0) (Kemptville, 2013) at the same fertilizer level and comparable yields to the 150N levels. In the clay loam soil, there was no statistical advantage to using any ESN blend treatment over straight urea, although the 75:25 urea:ESN blend tended to increase yields at all nitrogen levels. Chlorophyll index values generally increased with the increase in N application rates and were affected by the year (weather). Grain moisture content, test weight, and thousand-kernel weight were little affected by the N treatments. Soil residual N generally increased in drier years, 2011 and 2012, with higher N rates and with PCU blends. Our results show that the yield response to ESN is minor and inconsistent at the levels tested here. According to our results, the optimum N application rate is somewhere between

100 and 150 kg ha^{-1}; therefore, establishing N response curves with ESN blends might require additional intermediate rates between these two levels (e.g., 125 kg ha^{-1}) with more urea:ESN blend variations (e.g., 50:50 and 40:60). The environmental effects of using PCU should also be considered when making N fertilizer decisions, especially in lighter soils prone to leaching. In addition, replacing some of the pre-plant/early season urea application with PCU can be a feasible alternative to mid-season N applications; therefore, saving additional tractor passes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13030695/s1, Table S1: Leaf chlorophyll index as affected by nitrogen rate and source, measured at different development stages during the growing seasons at two experimental sites in eastern Canada (n = 8–11); Table S2: Yield and grain characteristics at harvest as affected by nitrogen (N) rate and source at two experimental sites in eastern Canada.

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Abbreviations

Environmentally Smart Nitrogen (ESN); Nitrogen (N); Polymer-coated urea (PCU); Residual soil mineral nitrogen (RN_{min}); Soil Plant Analysis Development (SPAD).

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