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Environmentally Smart Nitrogen (ESN)—Potential for Improving Modern Crop Production and N-Use Efficiency

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Abstract: Environmentally smart nitrogen (ESN) is polymer coated urea that is designed to release N in synchrony with crop requirements. Research on ESN was initiated in field crops in Ontario, Canada in 2006, initially on timothy, spring wheat and winter wheat and later (till date) on bromegrass, grass mixtures (timothy, bromegrass, orchardgrass), other forages (barley, silage corn, oat, MasterGraze corn and sorghum Sudangrass) and canola. In winter wheat, in three out of six years ESN gave ~0.6 MT/ha higher grain yield than urea. In spring wheat, in a relatively warm year with well-distributed rainfall, ESN produced 1 MT/ha higher grain yield than urea; averaged over three years, two-thirds N from urea and one-third N from ESN could be recommended. Two-thirds N from urea and one-third N from ESN gave ~0.75 MT/ha extra seed yield as compared to urea alone at 180 kg N/ha in canola during 2016 to 2018. The entire N in winter/spring wheat could be applied in seed rows at seeding as ESN without any detrimental effect. The highest barley forage yields were recorded by urea at 50 kg N/ha + ESN at 20 kg N/ha which produced 1.2 MT/ha more forage yield than urea at 70 kg N/ha. Partial substitution of N from urea with ESN improved forage dry matter yield of timothy and MasterGraze corn. In MasterGraze corn 100 kg N/ha from urea + ESN (3:1 on N basis) equaled that with urea at 150 kg N/ha in dry matter yield, % protein and relative feed value (RFV), but not in silage corn and sorghum Sudangrass. At equal rates of N, single/fall application of ESN in timothy and bromegrass gave equal yield to urea applied in two splits in spring/summer. Spring wheat grain yields were the same with fall/spring application of ESN. ESN/urea + ESN (3:1 on N basis) increased the grain/forage protein content in almost all crops by 1%-2% points at an extra cost of only $6.0-10.5/ha (with urea + ESN in 3:1 ratio on N basis). The results indicate that ESN could improve both crop yields and quality, make better use of N/or increase N-use efficiency. The paper summarizes results from over 10 years and the results could be applicable globally under situations of high N losses from readily available N sources such as urea.

Key words: Environmentally smart nitrogen, urea, spring wheat, winter wheat, barley, canola, timothy, bromegrass and MasterGraze corn.

1. Introduction

Environmentally smart nitrogen (ESN) is a patented technology of Agrium Inc. (name changed to Nutrien, https://www.nutrien.com/). It is polymer coated urea and contains 44% N (https://smartnitrogen.com/). The coating gives it a light green colour (Figs. 1 and 2). The polymer has micro-pores through which water enters, dissolves the urea and allows it to release slowly (Fig. 3). Nutrien claims that it can release N matching with crop requirements, about 8%-15% releases in the first 10 d, about 40%-60% N releases in the first month, about 85%-90% N releases within 60 d and offers a better alternative to urea [1]. Urea quickly hydrolyses in the soil and in 3-10 d; all the N supplied is converted into nitrate that is susceptible to leaching and denitrification under excessive soil water conditions. The first chemicals formed due to urea hydrolysis in soil are ammonium hydroxide and ammonium carbonate (in 2-4 d). Ammonium carbonate is a relatively unstable compound and could break into NH_3 (that is lost by volatilization) and H_2CO_3, which is further split to H_2O and CO_2 [2]. In addition, N losses from urea can also take place as surface runoff. Thus urea, from which a significant amount of N could be lost, is considered relatively a

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Fig. 1 Environmentally smart nitrogen (ESN) [1].

Fig. 2 ESN in the field [1].

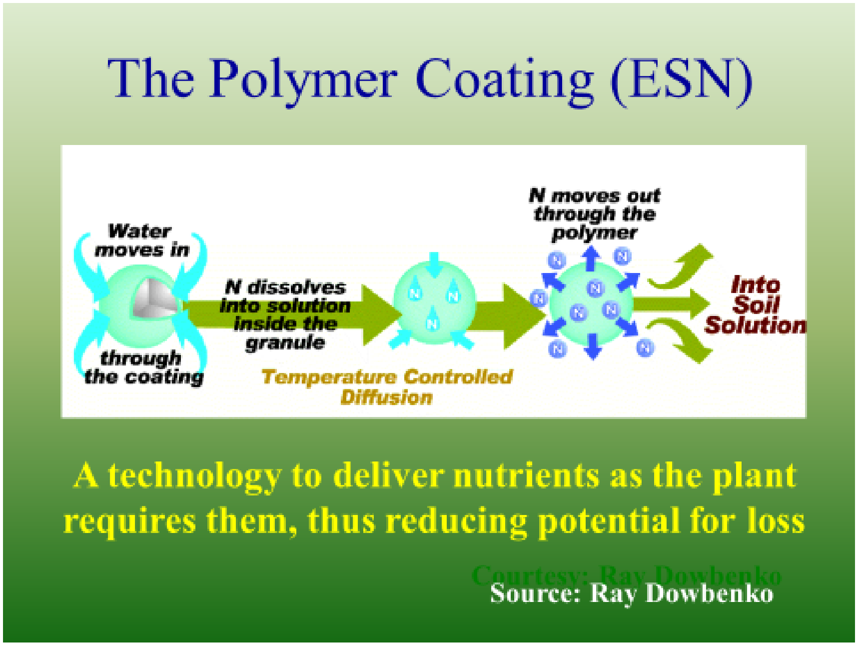

Fig. 3 N release from ESN [1].

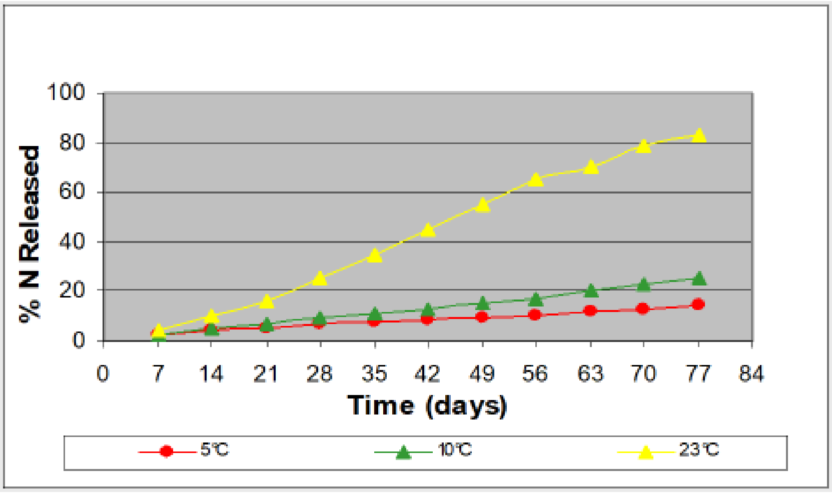

Fig. 4 N release from ESN as affected by temperature—Agrium, internal research, 2005 [1].

less efficient source of N than ESN. N-use efficiency was estimated to be less than 50% in the year of application [3, 4]. Another study had indicated that the N-use efficiency in the cereals worldwide was only 33% and that the ESN had the potential to significantly improve N-use efficiency while maintaining crop productivity [5]. On the other hand, N release from ESN which is temperature dependent (Fig. 4) could be too slow in the colder climates and it may not be an ideal N fertilizer in cold and short growing seasons such as in several parts of North America/Europe. A blend of the two fertilizers, urea and ESN, could prove better than either of the two fertilizers applied individually under such regions/growing conditions. Studies conducted on ESN in corn, wheat and other commodity grains elsewhere, especially in USA, indicated that ESN improved crop output per unit of applied N, reduced N losses to the environment and gave growers greater control over the fate of applied N [6]. These studies demonstrated that corn productivity with ESN could be maintained with 60%-75% of the N typically needed from traditional N fertilizers. However, there was no work done on ESN in the field crops in the Province of Ontario, Canada. Therefore, research on ESN was initiated in various field crops in 2006 to (i) find out the optimum rates of N from ESN alone or in its blends with urea and (ii) to determine its effect on the yield and quality of crop produce. Results from the research on ESN at the Thunder Bay Agricultural Research Station, Thunder Bay, Ontario, Canada (https://www.lakeheadu.ca/centre/luars) are reported in this paper.

2. Materials and Methods

Field experiments were conducted almost all in randomized complete block design (RCBD) with four replications in each experiment on forage (timothy, bromegrass, silage barley, MasterGraze corn, sorghum Sudangrass and silage corn), grain (spring and winter wheat) and canola to evaluate ESN or blends of ESN and urea as compared to urea at different rates of N application for crop productivity and quality at the Lakehead University Agricultural Research Station (LUARS), Thunder Bay, Ontario, Canada (48.38° N, 89.25° W; https://www.lakeheadu.ca/centre/luars), from 2006-2019. Experiments were also conducted to compare fall vs. spring application of N in grasses and spring wheat. Treatments in different experiments could be seen in Tables 1-13. The soil at the research station is silty clay loam, growing season is ~110 d and the crops are grown rainfed, without irrigation. Average soil test values in the plot ranges at LUARS were: soil pH 6.3, organic matter (OM) 4.1%, Olsen's P 34 ppm, ammonium acetate extractable K 184 ppm and cation exchange capacity (CEC) 23.1 meq/100 g. All N, unless specified otherwise, was applied pre

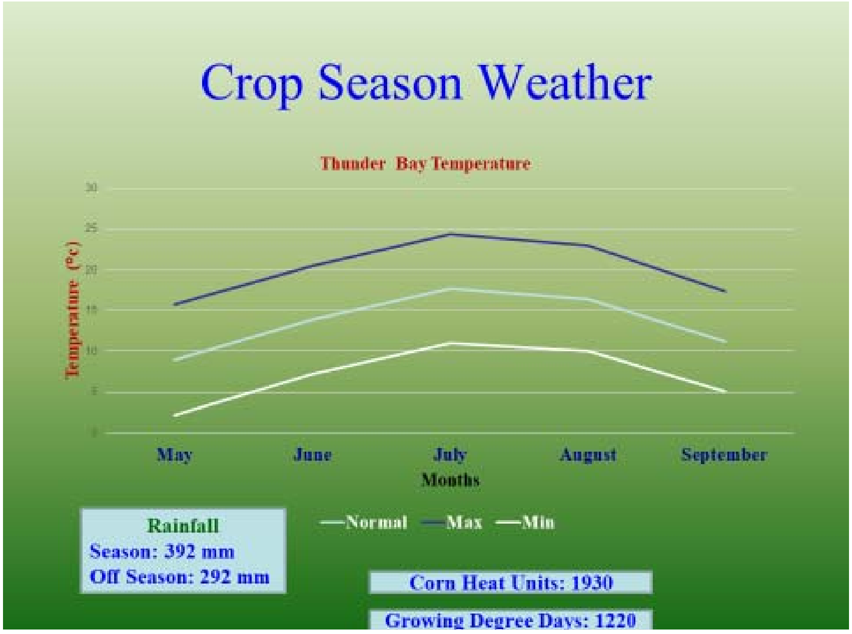

Fig. 5 Crop season weather at Thunder Bay, Ontario, Canada.

plant and incorporated into the soil at seeding. Other than the N treatments, all crops/experimental plots received recommended rates of other nutrients and uniform recommended crop production practices. Long-term averages indicate that maximum and mean day temperatures during the growing season (May-September) remain below 25 °C and 18 °C, respectively (Fig. 5). Total seasonal rainfall is nearly 400 mm. Corn heat units (CHU) and growing degree days (GDD) are 1,930 and 1,220, respectively. Plot size for the grain crops and canola was 3 m × 1.5 m and for the forage crops 6 m × 1.5 m. Crops were harvested at maturity/optimum stage and yields were reported in MT/ha. Results from all these experiments are reported in this paper.

3. Results and Discussion

3.1 Forage Crops

3.1.1 Forage Grasses

The first experiments to compare urea and ESN at 0, 35, 70 and 105 kg N/ha were initiated on timothy in 2006. Results based on three years (2007-2009) pooled analysis (total dry matter yield from two cuts, Tables 1 and 2) indicated that the response of timothy to urea exhibited a law of diminishing returns after 70 kg N/ha. With ESN, dry matter yield continued to increase up to 105 kg N/ha though the increase with every increment of N from 35 kg N/ha onwards was not significant. Percent N and protein in timothy increased only at the highest rate of N application (105 kg N/ha) both in urea and ESN though the increase was more with ESN than with urea. N removal was the highest at 105 kg N/ha, more with ESN (81 kg N/ha) than with urea (77 kg N/ha). Averaged over N rates, urea and ESN did not differ in dry matter yield, % N or protein content and N removal. Blends of urea and ESN did not give significantly higher dry matter yield, N or protein content and N removal than urea alone, though urea at 52.5 kg N/ha + ESN at 17.5 kg N/ha had 10 kg/ha higher N removal than urea at equivalent rate of N (70 kg N/ha) (Table 2). Residual effect studied in 2010 showed somewhat (357 kg/ha) higher dry matter yield with ESN than with urea (data not shown).

In another experiment on timothy and bromegrass (2008-2013), it was found that yield with ESN applied at 105 kg N/ha on September 25 equaled that with urea applied at the same rate of N in two splits (70 kg

N/ha in the fall on different dates or in the early spring and 35 kg N/ha applied after the first cut) (Table 3). Thus, fall application of ESN could save one field operation and avoid the risk of delay in spring application during wet springs. Interaction between the grass species and fertilizer treatments was non-significant; hence the results are presented only for the fertilizer treatments averaged over the two grasses (Table 3). Application of urea on October 25 or in the early spring and September 25 application of ESN produced equal protein content and all gave somewhat higher protein content than the check in the first cut. In the second cut none of the fertilizer treatments gave higher protein content than the check (no N). Bromegrass gave significantly higher dry matter yield than timothy in only two (2009 and 2012) out of five years (data not reported). In all other years, the yield from the two grasses was similar. Averaged over five years, dry matter yields from timothy and bromegrass were 4.13 MT/ha and 4.81 MT/ha, respectively.

In an experiment on mixed grasses (timothy 50%, bromegrass 42.5% and orchardgrass 7.5%, 2012-2015), application of N as urea or its blends with ESN and ammonium sulphate (AS) increased dry matter yield, protein content and N removal (Table 4). Increasing the rate of N from 105 kg N/ha to 140 kg N/ha improved the yield further. A blend of urea and ESN (3:1 on N basis) was no better than urea alone in increasing dry matter yield. However, the blend improved the protein content and N removal as compared to urea alone, especially at 140 kg N/ha, indicating better N-use efficiency from the blend of urea and ESN than urea alone. Adding AS to the urea and ESN blend further increased the dry matter yield by up to 1 MT/ha at both levels of N (105 kg/ha and 140 kg/ha), though not the protein content or N removal, which could be due to dilution effect of N with the increased yield.

3.1.2 Silage Crops

In an experiment on silage corn it was found that response to ESN was affected by seasonal temperature (Table 5). In a normal year (2010; CHU 2,081), there was no difference in dry matter yield from ESN and urea both applied at 150 kg N/ha. In a relatively colder year (2011; CHU 1,900), ESN produced lower dry matter yield than urea and in a warmer year (2012; CHU 2,131), ESN gave significantly higher dry matter yield than urea. Averaged over three years, dry matter yield from the two fertilizers was similar (urea 16.9 MT/ha and ESN 16.6 MT/ha). Blends of urea and ESN did not give better yield than the individual fertilizers alone in any of the years. Protein content in silage corn was not affected by the sources on N (data not shown). Residual effect of urea, ESN and their blends was studied on the following oat crop the next year(s). However, oat yield was not affected by the fertilizer treatments applied to silage corn (data not reported). It

Table 1 Effect of urea and environmentally smart nitrogen (ESN) on dry matter yield, N/protein content, and N removal in timothy at Thunder Bay—three years' pooled analysis (2007-2009).

Serial No.	Treatments	Dry matter yield (MT/ha)	N (%)	N removal (kg/ha)	Protein (%)
1	Check (0 kg N/ha)	2.55	1.80	35	11.1
2	Urea at 35 kg N/ha	3.18	1.70	50	10.6
3	Urea at 70 kg N/ha	4.10	1.80	72	11.5
4	Urea at 105 kg N/ha	4.12	1.90	77	12.0
5	ESN at 35 kg N/ha	3.24	1.80	50	11.0
6	ESN at 70 kg N/ha	3.85	1.80	63	11.0
7	ESN at 105 kg N/ha	4.21	2.00	81	12.4
Mean		3.61	1.80	61	11.4
Least significant difference (LSD) 0.05		0.65	0.1	13	0.9

Source: Sahota *et al.* [7].

Table 2 Effect of urea and ESN applied alone and in various blends on dry matter yield, N/protein content and N removal in timothy at Thunder Bay—three years' pooled analysis (2007-2009).

Serial No.	Treatments	Dry matter yield (MT/ha)	N (%)	N removal (kg/ha)	Protein (%)
1	Urea at 70 kg N/ha	4.60	1.51	72	9.4
2	ESN at 70 kg N/ha	4.44	1.43	68	8.9
3	Urea at 17.5 kg N/ha and ESN at 52.5 kg N/ha	3.94	1.59	65	10.0
4	Urea at 35 kg N/ha and ESN at 35 kg N/ha	4.55	1.56	74	9.7
5	Urea at 52.5 kg N/ha and ESN at 17.5 kg N/ha	4.98	1.58	82	9.9
Mean		4.50	1.53	72	9.6
LSD 0.05		0.67	NS	NS	NS

Source: Sahota *et al.* [8].

Table 3 Comparative effect of fall application of ESN and fall/spring application of urea on dry matter yield and protein content of timothy and bromegrass.

Serial No.	Treatments	Dry matter yield (MT/ha)*						Mean of protein % (2009-2013)	
		2009	2010	2011	2012	2013	Mean	1st cut	2nd cut
1	No N	2.73	2.81	3.97	3.37	2.36	3.05	12.6	13.3
2	Urea at 70 kg N/ha on Sep. 25	4.72	4.85	5.83	4.32	3.78	4.70	12.5	11.8
3	Urea at 70 kg N/ha on Oct. 10	5.07	4.30	5.44	4.83	3.80	4.69	12.8	12.4
4	Urea at 70 kg N/ha on Oct. 25	6.01	4.02	5.40	4.53	3.98	4.79	13.3	12.2
5	Urea at 70 kg N/ha on Nov. 5	5.27	4.49	5.36	4.66	3.95	4.75	12.8	13.1
6	ESN at 105 kg N/ha on Sep. 25	5.19	4.71	5.53	4.69	3.85	4.79	13.2	10.4
7	Urea at 70 kg N/ha in early spring (April 5-May 7)	5.64	4.89	5.46	5.56	3.85	5.08	13.6	12.2
LSD 0.05		0.58	0.97	0.61	0.59	0.43	-	-	-

*****Total from two cuts. In addition, 35 kg N/ha was applied after the first cut in all urea treatments.

Source: Sahota [9].

Table 4 Effect of urea and its blends with ESN and ammonium sulphate (AS) on mixed stands of grasses (timothy 50%, bromegrass 42.5% and orchardgrass 7.5%)—pooled over 2013-2015.

Serial No.	Treatments	Dry matter yield (MT/ha)	N removal (kg/ha) (1st cut)	Protein % (1st cut)
1	No N	2.44	27	12.1
2	105 kg N/ha from urea	4.09	73	16.9
3	140 kg N/ha from urea	4.65	83	16.6
4	105 kg N/ha: 78.75 kg from urea and 26.25 kg from ESN	4.11	72	16.5
5	105 kg N/ha: 58.25 kg from urea, 26.25 kg from ESN and 20.5 kg from AS	5.11	73	13.3
6	140 kg N/ha: 105 kg from urea and 35 kg from ESN	4.44	90	18.0
7	140 kg N/ha: 84.5 kg from urea, 35 kg from ESN and 20.5 kg from AS	5.50	90	15.2
LSD 0.05		0.44	7	-

Source: Sahota [10].

Table 5 Effect of urea, ESN and their blends (at 150 kg N/ha) on dry matter yield of silage corn yield (MT/ha).

Serial No.	Treatments	2010	2011	2012	Mean
1	Urea 100%	12.1	19.6	19.0	16.9
2	ESN 100%	11.0	15.7	23.0	16.6
3	Urea + ESN (1:3 on N basis)	10.9	16.5	18.5	15.3
4	Urea + ESN (1:1 on N basis)	10.8	16.2	18.1	15.0
5	Urea + ESN (3:1 on N basis)	11.9	15.9	18.1	15.3
LSD 0.05		NS	3.2	2.3	-

Source: Sahota [11].

was also found that the response to urea and ESN in grain corn in Quebec was influenced by weather [12]. In wet years (2008 and 2009), ESN resulted in higher grain yield than urea, whereas in a dry year (2010) no significant difference was found between urea and ESN. Effectiveness of the various enhanced-efficiency fertilizers would be strongly dependent on the environmental conditions [4]. Later research indicated that broadcast urea was as or more effective than broadcast ESN, split applications or blended (urea and ESN) applications in increasing corn dry matter yield under the wet conditions in the Lower Mainland ecoregion [13].

Three years (2013-2015) of pooled analysis from an experiment on urea and urea + ESN (3:1 on N basis) at different rates in MasterGraze corn and sorghum Sudangrass revealed that the dry matter yield and protein content from urea + ESN at 100 kg N/ha equaled that from urea at 150 kg N/ha (Tables 6 and 7). Thus there was a saving of 50 kg N/ha by replacing a part of N from urea with ESN. Increasing the rate of N from 150 kg/ha to 200 kg/ha did not increase the dry matter yield in MasterGraze corn or sorghum Sudangrass. Urea + ESN did not prove better than urea in sorghum Sudangrass; either in increasing dry matter yield or protein content (Tables 6 and 7). Protein content in MasterGraze corn was better with urea + ESN than with urea. The differing response of the two crops to ESN could be attributed to better/denser root system in sorghum Sudangrass than that in MasterGraze corn. Research on grain corn in Nebraska, USA, indicated that the ESN applied at 168 kg N/ha was as effective as split applied urea ammonium nitrate (UAN) at ~200 kg N/ha [14]. This study also observed that the chlorophyll content was significantly correlated to grain yield and that the chlorophyll content was consistently greater in ESN treatments than in UAN treatments, regardless of interannual climatic variations. These results indicated that ESN consistently performed better than UAN.

Application of 70 kg N/ha as urea or ESN or their blends with AS or a blend of the two together significantly increased the silage barley dry matter yield and improved protein content during 2013-2015 (Table 8). Urea at 50 kg N/ha + ESN at 20 kg N/ha and ESN at 60 kg N/ha + AS at 10 kg N/ha gave better yield than urea or ESN alone at the equivalent rate of N. A blend of the three fertilizers (urea at 40 kg N/ha + ESN at 20 kg N/ha + AS at 10 kg N/ha) improved the dry matter yield as compared to the blends of any two fertilizers though not significantly. ESN alone or in combination with urea resulted in a bit higher protein content than urea alone.

3.2 Grain Crops

Application of urea or ESN at 40, 80 and 120 kg N/ha did not increase the grain and straw yield of winter wheat as compared to the check (no N) during

Table 6 Effect of urea and urea + ESN at different rates of N on dry matter yield of MasterGraze corn and sorghum Sudangrass (pooled over 2013-2015).

	Dry matter yield (MT/ha)			
	MasterGraze corn		Sorghum Sudangrass	
N (kg/ha)	Urea	Urea + ESN	Urea	Urea + ESN
50	7.90	7.50	-	-
100	7.44	8.39	-	-
150	8.41	8.57	8.93	8.35
200	7.97	8.71	8.59	8.52
Mean	7.93	8.29	8.76	8.44
0 (no N)	6.13			
LSD 0.05		1.29		

Source: Sahota [15].

Table 7 Effect of urea and urea + ESN at different rates of N on protein content of MasterGraze corn and sorghum Sudangrass (pooled over 2013-2015).

	% Protein			
	MasterGraze corn		Sorghum Sudangrass	
N (kg/ha)	Urea	Urea + ESN	Urea	Urea + ESN
50	9.9	13.5	-	-
100	12.6	14.4	-	-
150	14.7	13.2	19.4	16.6
200	14.3	15.2	18.5	17.0
Mean	12.9	14.1	19.0	16.8
0 (no N)	12.7			
LSD 0.05	-			

Source: Sahota [15].

Table 8 Comparative efficiency of urea and ESN for barley silage production (dry matter yield and protein content in 2013-2015) at Thunder Bay.

Serial No.	Treatments	Dry matter yield (MT/ha)	% Protein
1	No N (Check)	4.78	9.6
2	Urea at 70 kg N/ha	5.85	10.7
3	ESN at 70 kg N/ha	6.01	11.1
4	Urea at 60 kg N/ha + AS at 10 kg N/ha	6.35	11.6
5	ESN at 60 kg N/ha + AS at 10 kg N/ha	6.69	10.7
6	Urea at 40 kg N/ha + ESN at 20 kg N/ha + AS at 10 kg N/ha	6.91	10.6
7	Urea at 50 kg N/ha + ESN at 20 kg N/ha	6.71	11.1
LSD 0.05		0.63	-

Source: Sahota [16].

2007-2010 (Table 9), because the average pre-seeding NO_3 test was 41 ppm (164 kg N/ha). However, grain protein content in winter wheat increased with an increase in N rates from 40 kg/ha to 120 kg/ha with both fertilizers (Table 9). Yields from urea and ESN were similar. In case of spring wheat, urea significantly improved the grain yield as compared to the check only at 120 kg N/ha, whereas ESN increased the grain yield significantly even at 80 kg N/ha. However, both urea and ESN at 80 kg N/ha increased the straw yield significantly over the check (no N). Increase in N from 80 kg N/ha to 120 kg N/ha from the two fertilizers did not further improve the straw yield. Averaged over N rates, grain and straw yields and grain protein content of winter and spring wheat were similar with urea and ESN.

A comparison of urea, ESN, AS and their blends was made on winter wheat during 2008-2011 with all of the N applied at seeding. Results are reported on the basis of pooled analysis for three years (Table 10). Among the three sources of N, the highest grain yield (5.47 MT/ha) was obtained with ESN at 120 kg N/ha. ESN and AS at 120 kg N/ha, but not urea at 120 kg N/ha significantly increased the grain yield over check (no N). Blends of urea with ESN or AS, except urea at 90 kg N/ha + AS at 30 kg N/ha, did not improve grain yield over urea alone. Grain yield from urea at 90 kg N/ha + AS at 30 kg N/ha equaled that with ESN at 120 kg N/ha. Increase in grain yield by blends of the three fertilizers in different proportions as compared to urea fell short of the level of significance. ESN and AS, but not urea, gave higher straw yield than the check (no N), though the increase was significant only with AS. Blends of urea and ESN did not improve the straw yield over urea or ESN alone, whereas blends of urea and AS or urea, ESN and AS produced significantly higher straw yield than urea at the same rate of N. The highest grain N removal (116 kg N/ha)

Table 9 Effect of urea and ESN on grain and straw yield of winter wheat and spring wheat at Thunder Bay (pooled over 2007-2010).

Serial No.	Treatments	Grain yield (MT/ha)		Straw yield (MT/ha)		Grain protein (%)	
		Winter wheat	Spring wheat	Winter wheat	Spring wheat	Winter wheat	Spring wheat
1	Check (0 kg N/ha)	5.07	3.32	7.24	4.47	11.8	15.0
2	Urea at 40 kg N/ha	5.06	3.53	7.29	4.75	11.8	16.5
3	Urea at 80 kg N/ha	5.35	3.55	7.37	5.16	12.5	17.0
4	Urea at 120 kg N/ha	5.60	3.65	7.75	5.25	13.3	17.5
5	ESN at 40 kg N/ha	5.11	3.28	7.27	4.49	11.6	16.3
6	ESN at 80 kg N/ha	5.19	3.67	7.51	5.02	12.4	17.0
7	ESN at 120 kg N/ha	5.42	3.69	7.43	5.00	13.2	16.7
LSD 0.05		NS	0.27	NS	0.32	0.60	-
Urea (mean over rates of N)		5.34	3.58	7.47	5.05	12.5	17.0
ESN (mean over rates of N)		5.24	3.55	7.40	4.83	12.4	16.7

Source: Sahota *et al.* [17] and Sahota *et al.* [18].

Table 10 Effect of urea, ESN, AS and their blends on winter wheat (pooled over 2008-2011).

Serial No.	Treatments-Source and N (kg/ha)	Grain yield (MT/ha)	Increase over check (MT/ha)	Straw yield (MT/ha)	Grain N removal (kg/ha)
1	0 (Check)	4.38	-	5.88	85
2	Urea 120	4.88	0.50	5.99	109
3	ESN 120	5.47	1.09	6.52	116
4	AS 120	5.11	0.73	6.87	107
5	Urea 30 + ESN 90	4.92	0.54	6.19	111
6	Urea 60 + ESN 60	4.67	0.29	5.89	98
7	Urea 90 + ESN 30	4.99	0.61	6.28	94
8	Urea 30 + AS 90	4.81	0.43	7.31	101
9	Urea 60 + AS 60	4.89	0.51	6.90	106
10	Urea 90 + AS 30	5.53	1.15	7.31	112
11	Urea 30 + ESN 45 + AS 45	5.36	0.98	7.41	114
12	Urea 60 + ESN 30 + AS 30	5.28	0.90	7.06	111
13	Urea 90 + ESN 15 + AS 15	5.24	0.86	7.08	113
LSD 0.05		0.66	-	0.83	14

Source: Sahota [19].

Table 11 Economics of ESN vs. urea.

Additional yield from ESN (as compared to urea)	587 kg/ha
Value of additional yield	$146.75/ha
Additional cost of ESN	$54.00/ha
Net benefit from ESN	$92.75/ha

Source: Sahota [19].

Table 12 Effect of fall vs. spring application of urea, ESN and their blends on spring wheat (pooled over 2014-2016).

Serial No.	Treatments	Yield (MT/ha)		Grain	
		Grain	Straw	N removal (kg/ha)	Protein %
1	No N (Check)	2.97	3.60	62	13.2
2	Urea 80 kg N/ha (fall)	4.15	5.06	99	14.3
3	ESN 80 kg N/ha (fall)	4.04	4.73	96	14.5
4	Urea 60 kg N/ha + ESN 20 kg N/ha (fall)	4.01	5.09	95	14.7

Table 12 to be continued.

Serial No.	Treatments	Yield (MT/ha)		Grain	
		Grain	Straw	N removal (kg/ha)	Protein %
5	Urea 40 kg N/ha + ESN 40 kg N/ha (fall)	4.38	4.98	105	14.6
6	Urea 80 kg N/ha (spring)	4.28	5.49	103	15.0
7	ESN 80 kg N/ha (spring)	4.27	5.09	102	15.3
8	Urea 60 kg N/ha + ESN 20 kg N/ha (spring)	4.46	5.52	104	14.6
9	Urea 40 kg N/ha + ESN 40 kg N/ha (spring)	4.18	5.02	98	15.1
LSD 0.05		0.48	0.54	12	-

Mean grain yield (MT/ha): urea—4.22; ESN—4.16; fall—4.15; spring—4.30. Mean N removal (kg/ha): urea—101; ESN—99; fall—99; spring—102.

Source: Sahota [20].

Table 13 Effect of urea and urea + ESN at different rates of N on canola seed yield (pooled over 2016-2018).

Serial No.	Treatments	Seed yield (MT/ha)
1	No N (Check)	2.88
2	Urea at 60 kg N/ha	4.49
3	Urea at 120 kg N/ha	5.05
4	Urea at 180 kg N/ha	5.92
5	Urea at 40 kg N/ha + ESN at 20 kg N/ha	4.32
6	Urea at 80 kg N/ha + ESN at 40 kg N/ha	5.81
7	Urea at 120 kg N/ha + ESN at 60 kg N/ha	6.66
LSD 0.05		0.50

Source: Sahota [21].

was recorded with ESN at 120 kg N/ha, which indicates higher N-use efficiency of ESN than that of urea and AS. Economics of ESN as compared to urea revealed that the net benefit from the use of ESN over urea was $92.75/ha (Table 11). It was reported from a multi-locational study in Western Canada that substitution of 50% or 100% of urea with ESN increased winter wheat grain yield by an average of 4.3% [22].

Effect of time of application (fall and spring) of urea, ESN and their blends at 80 kg N/ha was studied on spring wheat during 2014-2016. Pooled analysis of the data revealed that application of N irrespective of its source or time of application increased the grain and straw yield, grain N removal and grain protein content significantly as compared to the check (no N application) (Table 12). However, differences in grain or straw yield, grain N removal and protein content with the sources or blends of N and their times of application were not significant. However, the grain protein content and grain N removal seemed to be higher with spring application than with fall application of N. A few other researchers did not consider fall application of N as a better option than the spring application in the Gray/Dark Gray Luvisolic soil zone of Star city, Saskatchewan because they found that nitrous oxide (N_2O) loss was 1.5 fold lower from spring than from fall application [23]. The soils at Thunder Bay are Gleyed Gray Luvisol. Differences in response to fall vs. spring application of N between the two locations could be due to difference in winter conditions of the two places. Spring wheat grain yield in Manitoba was reported to be lower with fall than spring banded urea and the use of fall banded ESN reduced N losses and led to yields intermediate between fall and spring banded urea. Grain protein occasionally increased with use of ESN vs. urea fertilizer [24].

3.3 Canola

Urea and urea + ESN (3:1 ratio on N basis) were compared at 0, 60, 120 and 180 kg N/ha in canola during 2016-2018. Pooled analysis of the data over years indicated that the response of N to canola was linear up to 180 kg N/ha both with urea and urea + ESN (Table 13). Increase in seed yield over check (no N) was significantly more with urea + ESN than with urea at 120 kg N/ha and 180 kg N/ha. Seed yield from urea + ESN at 180 kg N/ha was 6.66 MT/ha as compared to 5.92 MT/ha from urea at 180 kg N/ha. The results show that it pays to blend urea and ESN for canola production. These results differ from those of some others whose research in the semi-arid Mixed Grassland, moist Aspen Parkland or wet Boreal Transition ecoregions showed that urea applied as an in-soil band at the time of seeding was generally as or more effective than similarly placed ESN, split application of urea or blended urea and ESN in increasing early season dry matter yield and seed or grain yield of canola, wheat or barley [13]. However, they did indicate that there were some situations where use of split applications or use of the ESN in a blend with the non-coated urea resulted in increases in grain yield as compared to the non-coated urea, primarily under moist conditions in the Boreal Transition or Aspen Parkland ecoregions. While they had band applied N fertilizers, the fertilizers were broadcast and incorporated in the soil at Thunder Bay (in this study). Band application would be expected to reduce losses from the urea and reduce the comparative benefits of ESN as compared to urea. It was found that the emergence, seed yield and N uptake in durum wheat and canola in Saskatchewan were generally greater with coated urea (ESN) than with non-coated urea and the coated urea was relatively safer for seed row placement [25].

Benefits in grain yield and protein content from ESN or urea + ESN blends could be attributed to better and prolonged N supply from ESN as compared to other N fertilizers, especially urea. ESN potentially provided improved N-release timing (by releasing N into the soil over an extended period of time, matching plant need) and better potato yields as compared with urea in Idaho, USA [26]. They also observed that soil temperature controlled N release rate and simultaneously influenced plant growth. N-fertilizer use efficiency (FUE) could be enhanced by certain modifications to urea [27]. Slow and controlled release and stabilized fertilizers were an option for enhancing nutrient efficiency in agriculture [28]. N_2O loss in small grains was 1.5-1.7 fold higher from urea than ESN at Star city, Saskatchewan [23]. Controlled-release and stabilized N sources had the potential to reduce N_2O emissions from irrigated no till cropping systems when compared with dry granular urea [29]. N_2O fluxes resulting from urea application peaked within days after application, whereas N_2O flux peaks from ESN occurred 4-6 weeks after application but with flux peaks of lower magnitude than with urea; ESN reduced N_2O emissions by 49% compared with urea [29]. In later studies, it was found that the ESN reduced N_2O emissions by 42% compared with urea and 14% compared with UAN in no-till and strip-till environments [30]. A review of the work on enhanced efficiency and controlled-release fertilizers, nitrification inhibitors and urease inhibitors on rice, corn and wheat cropping systems concluded that the controlled-release fertilizers consistently reduced N_2O emissions compared with conventional N fertilizers across soil and management conditions; grand mean decreases of 38%, 30% and 19%, respectively, in the three cropping systems [31]. A similar review by another researcher also indicated potential of increasing crop productivity while limiting environmental N losses using enhanced efficiency fertilizers including coated fertilizers such as ESN [32]. Based on a summary of laboratory, glasshouse, and field research trials it was reported that polymer coated urea (ESN) resulted in significantly less N loss from soil to the air and, potentially, to the water compared to uncoated urea [33]. Average ammonia volatilization and N_2O emissions were lower for ESN by 300% and 120%, respectively. It was also observed that ESN resulted in crop yields and/or quality which were significantly improved or at least equivalent to uncoated urea when managed properly in these studies [33]. Another advantage from ESN over urea, apart from reducing N losses, was that during 75% of the times it increased microbial biomass or functional diversity more than urea [34].

Enhanced efficiency fertilizers are continuously being developed to regulate the release of N from fertilizers, allowing for improved uptake and utilization by plants, thereby lowering losses and increasing crop productivity per unit of fertilizer [27]. Enhanced efficiency fertilizers have the potential to improve synchrony between nutrient supply and crop uptake, reduce nutrient losses and improve nutrient use efficiency [3]. Overall, the studies on ESN suggest that the global use of ESN could greatly mitigate environmental risks related to air and water quality while meeting the demands for providing food, fuel and fiber for the seven billion plus people on earth [33].

4. Conclusions

As may be seen from the results and discussion, response to ESN or blends of urea and ESN varied with the weather and crops. However, blends of urea with ESN improved crop yields, protein content and nutrient removal (better nitrogen use efficiency) in most crops/cases at a nominal cost as compared to urea. In winter wheat which has a longer growing season than spring-seeded annual crops, ESN without its blends with urea proved to be better than urea. The increases in yields by ESN or urea + ESN over urea were economically rewarding. Thus, use of ESN either alone (in longer duration crops) and in blends with urea (in short duration crops) could be encouraged for crop production particularly in situations where environmental conditions promote N losses from denitrification and leaching.

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