Main factors affecting nutrient and water use efficiencies in spring canola in North America: A review of literature and meta-analysis

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Abstract

Improving nutrient and water use efficiencies through optimizing field management practices are essential strategies to increase economic and environmental sustainability of the canola production industry in North America. The objective of this study was to review recent research publications and quantitatively assess the impact of field management practices on the efficiency of water and selected macro-nutrients (nitrogen, phosphorous and sulphur) in canola and to identify the most effective cultural practices for improved efficiencies. For this, a meta-analysis was performed using 730 comparisons extracted from 24 peer-reviewed publications. Results showed that, overall, the addition of nitrogen (N) and sulfur (S) inputs in studies across North America had a negative impact on nitrogen use efficiency (NUE) and sulphur use efficiency (SUE) as compared to corresponding controls. Among the nine field management practices evaluated, only a study combining N source, placement, and timing improved NUE marginally (7.5%). Among the four sulfur management combinations analyzed, only applying N with S fertilizer led to a significant increase in SUE (30%). The use of S in SO_4 form in combination with an appropriate N source is an effective strategy for improved SUE in canola. Among the nine water management combinations reviewed, three management practices, namely irrigation at defined growth stages (48.5%), maintaining stubble height (11.4%) and time of stubble incorporation (6.3%) had a significant positive impact on water use efficiency (WUE). Maintenance of adequate soil moisture conditions throughout reproductive development of the canola crop through supplementary irrigation and/or stubble management is important for improved WUE. The effects of supplementary irrigation (3.6%) and irrigation rate (9%) were marginal, but also positive. Phosphorus use efficiency was excluded from our meta-analysis, due to a lack of sufficient publications related to canola in North America. The lack of positive impacts of many management practices on NUE, SUE and WUE suggest that further research is required on the integration of canola genotypes with improved nutrient and water use efficiencies and effective management practices to improve economic sustainability in North America. Development of new canola genotypes with desirable traits associated with nutrient uptake and drought tolerance may play a key role in this endeavour.

1. Introduction

Canola (*Brassica napus* L. and *Brassica campestris* L.) is the second largest field crop grown in Canada, with 8.4 million ha seeded in 2020 and 99.4% of the total production is confined to the Canadian Prairies (https://www150.statcan.gc.ca/n1/daily-quotidien/190626/dq190626b-eng.htm). The USDA National Agricultural Statistics Service estimated about 0.81 million ha of canola seeded in USA in 2019 with an average productivity of 4,000 kg ha^{-1}. In 2019, the Northern Great Plains (North Dakota and Minnesota) produced 84 % of canola in the USA with 0.71 million ha planted. The Pacific Northwest (Idaho, Oregon, Montana and Washington) accounted for about 26,300 ha (https://www.uscanola.com).

Since the inception of the Green Revolution, there has been a significant increase in the use of inputs in agricultural food production systems worldwide, particularly nitrogen (N) fertilizer (Hartmann et al., 2015; Tian, 2017). It has been projected that the global human population will reach 9.7 billion by 2050 (United Nations, 2019), hence food production and distribution will be a crucial challenge for feeding the predicting population. The global utilization of synthetic nitrogen fertilizer in 1961 was 11.3 Tg N (Lu and Tian, 2017), and the demand in 2020 has increased to 108.7 Tg N (FAO, 2019), which is a 9.6-fold increase over the past six decades. Depending upon the crop species, the elimination of N application would reduce crop yield by 16% for wheat to 41% for corn in U.S.A (Smith et al., 1990), indicating that N fertilizer is a vital input for maintaining crop production and mitigating food production risks (Cassman et al., 2002; Stewart and Roberts, 2012). Although N fertilizer is known to increase seed yields of various crop species (Heisey and Mwangi, 1996; Hawkesford, 2014; Ngezimana and Agenbag, 2014), excessive N application has produced adverse effects on crop, soil, environment and ground water quality (Ladha et al., 2005; Hartmann et al., 2015; Cui et al., 2018; Liang et al., 2018; Zhang et al., 2018). Consequently, a balance between N input and N use efficiency must be maintained for sustainable crop production (Chen et al., 2014; Zhang et al., 2016; Cui et al., 2018; Ding et al.,2018). Crop input usage is influenced by crop species and input prices, perceptions, input efficacy and grower attitudes towards innovation and risk.

Canola requires higher amounts of nitrogen than wheat and barley (Grant and Bailey, 1993; Brennan et al., 2000; Brennan and Bolland, 2009). Most prairie soils are deficient in plant-available N, and N fertilizer is normally needed to attain high yield and quality of canola (Grant and Bailey, 1993). Many studies in western Canada have focused on the seed yield response of canola and canola-quality *B. campestris* L. cultivars to N fertilizer (Racz et al., 1965; Ridley, 1972; Henry and MacDonald, 1978; Nuttall et al., 1987; Bailey, 1990) and show a significant increase in yield and/or economic returns from applied N, depending on growing conditions and the level of soil test NO_3-N (Soper et al., 1971; Nyborg et al. 1999). Although *B. campestris* cultivars generally have lower yield potential than *B. napus* cultivars, breeding efforts have significantly improved the agronomic traits and yield of new cultivars, particularly hybrids, compared with those grown earlier (Saskatchewan Agriculture and Food 2000). As an increased supply of nutrients is typically required to support higher yields, fertilizer rates and other crop management practices may need to be re-evaluated to ensure that the improved genetic potential is consistently realized. This also suggests the possible need for separate management recommendations for specific canola cultivars.

Nitrogen use efficiency (NUE) may have different definitions, but it is commonly defined as seed yield that is produced per unit of available N (Gan et al., 2008). Total NUE can be further partitioned into nitrogen uptake efficiency (NUpE), which is defined as the ability of the plant to capture N from the soil in relation to the amount of the N added to the soil (Maaz et al., 2016) and nitrogen utilization efficiency (NUtE), the ability to utilize the absorbed N to produce seeds and it is calculated as total seed dry weight divided by N content (Balint and Rengel, 2008). Nitrogen uptake efficiency includes trait effects, such as root morphology and transporter activity, while NUtE is the effect of all processes that contribute to the capacity of the plant to assimilate and remobilize N into the seeds (Bouchet et al., 2016).

Although selecting new crop cultivars and identifying the optimum N application rate are being used to improve NUE in wheat, barley, and canola (Gan et al., 2008; Malhi et al., 2010; Hawkesford, 2014; Hartmann et al., 2015; Smith et al., 2019), field management practices for better N utilization must also be developed, as crop management practices can affect NUE differently among crop species, including canola and wheat (Malhi et al., 2006). Applying N fertilizer in excess of what the canola crop requires can be harmful because this encourages lodging, reduces seed yield, and seed quality by decreasing oil content and increasing chlorophyll content of the seed, and increases production costs. The application of excess N fertilizer also reduces nitrogen use efficiency (NUE) as a large portion of applied N can be subject to volatilization, denitrification, surface and subsurface runoff, and stabilization into soil organic matter and clay colloids, and consequently increased N losses from the agro-ecosystem (Heaney et al., 1992; Nyborg et al., 1997; Raun and Johnson, 1999; Brennan et al., 2000; Karamanos et al., 2003; Rathke et al., 2005; Wu and Ma, 2016; 2018). As a result of these risks, expansion of canola production in eastern Canada is highly dependent on the development of regional or site-specific guidelines for environmentally sound N management that focus on improving NUE (Ma and Herath, 2016).

The importance of early season phosphorus (P) nutrition for optimum seed yield is well known for canola (Grant et al., 2001; 2009), however the reduction in early season growth from inadequate P supply does not always affect seed yield (Grant et al., 2001). It is often assumed that P limitation later in the season has a much smaller impact on crop production than do limitations early in the growing season (Grant et al., 2001). Over-fertilization of P raises the risk of water pollution, leading to eutrophication and algal blooms in lakes and streams. Therefore, improving phosphorous use efficiency (PUE) is important for the economic production of canola and sustaining environmental quality (Korkmaz and Altintas, 2016). Similar to small grain cereal crops, canola requires P to maximize yield, however, it requires modest P applications due to the high efficiency of canola in scavenging both soil P and applied P (Brennan and Bolland, 2009). The fertilizer P requirements for profitable yields were generally obtained by varying P addition, separately or combined with different N rates, to determine P accumulation and seed yield responses. Previous studies indicated that NH_4^+ fertilizers largely stimulate P uptake in canola and higher seed yields and effectiveness of P fertilizers could be achieved when P applied with

NH_4-N sources (Brennan and Bolland, 2007; 2009). Furthermore, a recent study conducted in Ontario, Canada showed that under adequate soil P supply conditions, P uptake in canola was largely enhanced by N additions, especially at higher rates of N (Ma and Zheng, 2016).

Sulphur (S) is an essential component of the amino acids, cysteine, and methionine in plants, and the Brassicaceae family generally require larger amounts of S than wheat and barley (Nuttall et al., 1987; Grant and Bailey, 1993) to synthesize sulfur-containing secondary metabolites called glucosinolates (Haneklaus et al., 2007). The interactive effects of N and S on canola yields have been demonstrated, with a conclusion that N fertilizers encourage S uptake, and that N and S applications must be in balance to achieve optimum seed yields of canola grown in S-deficient soils (Jackson, 2000; Malhi et al., 2007; Malhi and Gill, 2007). In western Canada, it is recommended that S be applied in a fertilizer mixture having an N to S ratio of 5 to 1 to 7 to 1 (Karamanos et al., 2007). In contrast, in eastern Canada, field crops are rarely fertilized with S because S is available from human-caused sources of S from air-borne pollution and inherent soil S reserves. Environment Canada measured SO_4-S deposition levels ranging from 5.6 to 11.2 kg S ha^{-1} in 1990, but only approximately 3.4 kg S ha^{-1} in recent years (OMAFRA, 2018). Ma et al. (2019) reported that fertilizer S application greatly improved seed canola seed yields at six out of nine site-years, and the highest N use efficiency was in the N150 +S20 kg ha^{-1} treatment suggesting the importance of S supplement when high N rates are applied for canola production in eastern Canada. Hammac et al. (2017) found that water and temperature variability played a larger role than soil nutrient status, particularly N and S on canola grain constituents and seed yield in Northwest U.S.A.

While irrigation development has increased crop productivity in soil moisture deficit semi-arid regions in the Canadian Prairies for decades, water scarcity and escalating costs of investing in and managing the infrastructure could hinder further expansion of irrigation. Increasing demand for water by households, mining and industries combined with anticipated changes in rainfall patterns, has forecast water shortages that limit future irrigation development. Subsequently, there is need for new approaches for agriculture to keep pace with rising demand for food and fiber while applying the lowest possible amounts of irrigation. To achieve better use of water, the production of dry matter or marketable crop must be increased per unit of water used in evapotranspiration and for irrigation in semi-arid and desert areas (Viet, 1962). Water use efficiency (WUE) has been defined different ways. Earlier, WUE was defined as the amount of carbon assimilated or crop yield per unit of transpiration (Viet, 1962) and later as the amount of biomass/marketable yield per unit of evapotranspiration. Irrigation scientists describe WUE as a ratio of total supplied water transpired to water diverted from the source, whereas crop researchers define it as the ratio of total biomass/grain yield to water supplied (Israelsen, 1932; Sharma et al., 2015). The authors of the publications reviewed for this manuscript, defined the WUE as the ratio of seed yield produced to the total amount of water made available to the crop (rainfall and irrigation water).

A meta-analysis is a statistical method that can be used to comprehensively evaluate the effects of a given agronomic practice, such as fertilizer application and irrigation, and or/ or genetic factor on a large scale and can help explain the causes of variations (Bigerna et al., 2017; Gurevitch et al., 2018). In their review and interpretation, Assefa et al. (2018) summarized the major management factors determining spring and winter canola yield in north America and subjected some of these factors to a meta-analysis. They identified rainfall/irrigation, latitude/radiation, soil properties/soil nutrient/fertilizer, temperature, and length of growing season as the factors with the greatest impact on canola yield. The only other meta-analyses found for canola in our review of recent literature focused on canola oil or meal in human and animal feeding studies.

The objectives of this study were to, i) assess the effect of fertilizer inputs (N, P, and S), applied as single or combination treatments, irrigation and indirect soil moisture management (stubble management and tillage) on the nutrient and water use efficiencies of canola; ii) understand the influence of field management practices on these nutrients and water use efficiencies, iii) provide recommendations for future research and iv) identify suitable strategies to improve canola production efficiency in North America.

2. Materials and methods

2.1 Data search and collection

Recent peer-reviewed publications were compiled by searching Google Scholar and the University of Lethbridge Library database by using the following keywords: 'Canola', ˈNorth Americaˈ, ˈNUEˈ, ˈWUEˈ, ˈwaterˈ, ˈnitrogenˈ, ˈsulphurˈ, ˈirrigationˈ, and ˈseed yieldˈ. To avoid any bias, previous publications were selected according to the following criteria: i) the field experiment must have been conducted in North America; ii) the cropping system in the field experiment must contain spring Argentine canola (*Brassica napus* L.); iii) the study included one or more of the following management-related factors: N fertilizer rates, S fertilizer rates, irrigation, and soil moisture management; iv) studies reported seed yields, v) treatments must have been replicated and randomized; and v) if one study reported different years or site-year observations within the same experiment, each year or site-year observations were considered as separate observations (van Groenigen et al., 2013). Accordingly, a total of 24 publications were incorporated into our dataset. The dataset consisted of 355 measurements for NUE from 12 peer-reviewed publications from 2008 to 2020, 276 measurements for SUE from 4 peer-reviewed publications from 2002 to 2020 and 99 measurements for WUE from 8 peer-reviewed publications from 2004 to 2020.

2.2. Data processing

Nitrogen use efficiency was calculated as:

$$NUE = \frac{Y}{N} \tag{1}$$

where NUE is the nitrogen use efficiency (kg kg^{-1}), Y is the crop yield (kg ha^{-1}), and N is the amount of N (kg N ha^{-1}) applied as fertilizer and soil N if reported.

Water use efficiency was calculated as:

$$WUE = \frac{Y}{W} \tag{2}$$

Where WUE is the water use efficiency (kg m^{-3}), Y is the crop yield (kg ha^{-1}) and W is the total amount of irrigation water and rainfall (mm), representing total water input.

Sulphur use efficiency was calculated as:

$$SUE = \frac{Y}{S} \tag{3}$$

where SUE is the Sulphur use efficiency (kg kg^{-1}), Y is the crop yield (kg ha^{-1}), and S is the amount of S available in soil plus S applied as fertilizer (kg S ha^{-1}).

Nitrogen use efficiency values were grouped into ten categories: Method of N application (urea spring band vs. combinations of N source (CRU and a blended mixture) and placement method (spring-banded, fall-banded and split application), N rate, species by (*B. napus* vs. other species) N rate, year by N rate, N source (Urea vs. CRU) by N rate, S rate by N rate, stubble management (stubble retained or incorporated) by N rate, fertigation stage (no fertigation vs. other) by N rate, variety by N rate, timing (pre-plant vs. side dressed) by N rate.

Water use efficiency values were grouped in to nine categories: Irrigation at different growth stages (rain-fed vs. partially or fully irrigated), stubble height (no stubble at seeding vs. stubble maintained at different heights and seeding), irrigation rate (rain-fed vs. different amounts of irrigation), time of stubble management (no stubble in spring vs. stubble at different heights either in spring or fall), irrigation (rain-fed vs. irrigated), row spacing by stubble height [30-cm apart with 15-cm stubble height vs. wider spacings with taller (>15 cm) stubble heights], species by water regime (*B. napus,* well-watered vs. other species, rain-fed or no precipitation), species by seeding date (*B. napus* seeded early spring vs. *B. napus/B. campestris* seeded late spring or late fall), species by stubble management (*B. napus* on fallow vs. *B. napus* on stubble or *B. campestris* on fallow or -stubble).

Sulphur use efficiency values were grouped in to four categories: N rate by S rate, application timing by growth stage by S rate (incorporated at seeding vs. side-banded and seed row placed at seeding and top-dressed or foliar applied at bolting and early flowering), S rate (no S applied vs. different rates of S applied), timing by source by S rate (spring-applied ammonium sulphate at 10 kg S ha^{-1} vs. spring/fall applied S in various fertilizer forms applied at two rates (10 or 20 kg S ha^{-1}).

2.3. Meta-analysis

Meta-analysis is a formal quantitative statistical method to summarize results from independent experimental studies (Li et al., 2021). In our study, we used the effect size (R) to quantify the effect of different field management practices alone or combination with canola varieties or species on crop NUE, WUE and SUE.

$$R = \frac{\bar{X}e}{\bar{X}c} \tag{4}$$

Where $\bar{X}e$ is the mean of the treatment group and $\bar{X}_c$ is the mean of the control group practices. To express the treatment effect on a common scale, the natural logarithm of the response ratio was used (Li et al., 2021):

$$\ln R = \ln\frac{\bar{X}e}{\bar{X}c} = (\ln\bar{X}_e - \ln\bar{X}_c) \tag{5}$$

Most of the studies considered in our compilation have reported experimental design with the number of replicates, but not the standard deviation or standard errors. To include as many studies as possible, we performed analysis using non-parametric weighting functions (Lu, 2020). The weighting factor for each effect size was calculated as follows (van Groenigen et al., 2013):

$$W_i = \frac{(ne \times nc)}{(ne + nc)} \tag{6}$$

where W_i indicates the weight of ^{i}th lnR and n_e and n_c represent the number of replicates of treatment and control, respectively. Higher weighting is given to well-replicated studies with larger sample sizes under these conditions. When multiple effects were extracted from the same experimental site, we adjusted the weights defined above by the total number of observations from that site. This approach ensured that all experimental comparisons in multi-factor and multi-year studies could be included in the dataset without dominating the overall effect size (Li et al., 2021). Thus, the final weights (wfi) used in the analyses were as follows:

$$wfi = \frac{Wi}{nsite} \tag{7}$$

where n_{site} is the number of observations from the same site as the i^{th} observation. The weighted average of the logarithmic response ratio was calculated for all independent studies as shown below:

$$\mathrm{lnR} = \frac{\sum_{i=1}^{m} wfilnRi}{\sum_{i=1}^{m} wfi} \qquad (8)$$

where lnRi is the logarithmic response ratio for the i^{th} comparison, m is the number of studies, and lnR is the mean effect size (Li et al., 2021).

To simplify the interpretation, the mean effect size (MES) was expressed as the percentage change as follows:

$$\mathrm{MES\%} = (e^{\mathrm{l}\bar{\mathrm{n}}\mathrm{R}} - 1) \times 100\% \qquad (9)$$

In the meta-analysis, a confidence interval CI of 95% was used to determine the level of significance. If the values of the 95% CI for the effect size of a variable did not overlap with zero, the effects of management practices on the variable studied were considered statistically significant; otherwise, the treatment effect was not significant (Li et al., 2021).

2.4. Statistical analysis

We used Microsoft Office 2016 (Microsoft, USA) to collect and tabulate data of our study. The meta-analysis was conducted using Comprehensive Meta-Analysis software v3. (Biostat Inc. USA).

3. Results and Discussion

3.1 Nitrogen use efficiency (NUE) of canola

Determination of NUE is an important approach to evaluate the fate of applied N fertilizers and their role in enhancing canola yield and minimize production costs (Ma and Herath, 2016). Optimizing NUE is challenged by interactive effects such as physiological, ecological, and agronomic factors (Maaz et al., 2016). Due to the high demand for N, high rates of N fertilizer are commonly applied to canola to achieve maximum seed yields (Balint and Rengel et al., 2008). Canola has relatively low NUE because of poor N utilization in tissues rather than low efficiency in N uptake from soil. Poor N utilization in tissues results in a low N- harvest index mainly through seed sink limitations (relatively low yield potential and small seed harvest index) and partially due to the fall of N-rich leaves (Svecnjak and Rengel, 2006). Thus, fine-tuned N nutrition together with the identification of cultivars with enhanced NUtE are of commercial interest due to better use of N fertilizers and may increase crop yield (Balint and Rengel, 2008). Improving NUE of Canola is crucial in the development of sustainable agricultural systems to optimize crop productivity in an economically and environmentally responsible manner (Bouchet et al., 2016; Ma and Herath, 2016). Important management factors that affect NUE in a crop production system include weather, water availability, tillage practices, residue retention, crop rotation, and fertilizer rate, timing, placement, and source (Maaz et al., 2016).

NUE estimates are useful for establishing yield-based N recommendations and characterizing a system's production efficiency. The NUE component analysis identifies plant and soil activities that contribute to differences in seed yield in response to N. The NUE components include N retention efficiency, available NUpE, NUtE, seed N accumulation efficiency, and N harvest index. In a component analysis, NUE is calculated to evaluate the differences in cropping systems (Maaz et al., 2016).

3.1.1 Rates of N fertilizer application vs. nitrogen use efficiency

In comparison with wheat and barley crops, canola production requires high inputs, especially N. As a non-legume oilseed crop, canola also has a higher demand for N fertilizer per unit seed yield than other oilseed crops (Balint and Rengel, 2008; Bouchet et al., 2016). Nitrogen fertilizers are essential to increase canola yields and N accounts for the highest energy use and input cost in oilseed cultivation systems (Ma and Herath, 2016; Ma et al., 2019). However, N application in excess of canola requirements can increase chlorophyll content of the seed, increase N losses from the agroecosystem, induce crop lodging, and reduce seed yield and quality by decreasing oil content (Ma et al., 2019). Lafond et al. (2008) reported that in the western Canadian prairies, applying 50% of N in-season can efficiently match N requirements and reduce the risk of N leaching (Ma and Zheng, 2016). This suggests that N applications may not yet be optimized for canola production.

The NUE typically declines with progressively increasing N supply which is an outcome of nutrient responses that follow Mitscherlich's law of diminishing returns in agricultural systems. An example of this relationship is shown in Figure 1 which has been adapted from Malhi et al. (2007). Assefa et al. (2018) concluded that canola yield plateaus when available N reaches 100 to 200 kg ha^{-1}, depending on the environment. Nitrogen losses can occur with increasing N supply due to crop plants approaching the physiological inefficiencies of N use (Gan et al., 2008). In addition, excessive N application increases production costs due to the high fertilizer price and low NUE, and due to the vulnerability of N fertilizer loss during the growing season via volatilization, denitrification, surface and subsurface runoff and stabilization into soil organic matter by clay colloids (Ma et al., 2012). Ma and Zheng (2016) suggested that the optimum rate of N fertilizer for canola production is ~150 kg ha^{-1} in humid regions such as eastern Canada and higher yield and/or NUE and can be obtained when N fertilizer is side-dressed, under normal weather conditions. Similar results for N application on Canola NUE were examined in western Canada (Gan et al., 2008) and in Australia (Ma and Herath, 2016). Brassica oilseed crops respond to N fertilizer positively even if applied at rates as high as 180 kg N ha^{-1}, but the amount of N fertilizer required for maximum yield of oilseed species differ, depending on environmental conditions (Brandt et al., 2002; Assefa et al. 2018).

A field study conducted at 11 sites in Saskatchewan from 2003 to 2005 showed that there was a general trend of decreasing NUE with increasing N fertilizer rate in all five of the oilseed species studied, including *B. napus*. Maximum NUE was obtained at the N fertilizer rates up to 100 kg N ha-^{1} less than the rates required to maximize seed yield (130 kg N ha^{-1}). Furthermore, the study reported that the magnitude of decrease in NUE with increasing rates of N fertilizer was interactively influenced by soil N supply and rainfall during the months of vigorous vegetative growth and flowering period. Therefore, optimizing rates of N fertilizer under different environmental conditions, soil N supply, and rainfall is necessary for improving NUE in canola production (Gan et al., 2008).

3.1.2 Timing of N fertilizer application vs. nitrogen use efficiency

Timing of N application has a significant impact on the N economy, including agronomic N-use efficiency (aNUE) and its components, NUpE, NUtE, partial N balance, and N harvest index of canola (Ferguson et al. 2002). The optimization of timing of N application is a must for developing nutrient best management practices to improve NUE (Ma and Zheng, 2016). For instance, applying excess N to canola prior to planting can increase N losses due to less demand for N at the early stages of plant growth (Ferguson et al., 2002). Canola yield is associated with growing-season dry matter (DM) accumulation (Karamanos et al., 2005). In canola, the greatest DM accumulation is during flowering. In addition, the effect of N fertilizer on canola yield partially depends on the capacity of the crop to mobilize N from senescing vegetative organs to seeds. Seed yield and the DM content could be affected by the timing of N application, however contradictory results were reported (Ma and Zheng, 2016). A previous study indicated that, under humid eastern Canadian conditions, side dressed N application at the 6-leaf stage was more effective in improving crop N uptake and provides better N economy in comparison with an equal amount of N received entirely at the preplant stage (Ma and Herath, 2016). Therefore, split application can be more productive because it provides N at the suitable stages during crop growth (Ma and Herath, 2016). In contrast, studies conducted in western Canada under arid and semi-arid conditions by Grant et al. (2012) showed that split applications of N were no more effective in both DM and yield than all N applied at seeding. In addition, the rates and timing of fertilizer N required to maximize the yield of canola depend on environmental conditions (Ma and Herath, 2016). Therefore, a better understanding of the underlying changes in seasonal DM and N accumulation and utilization in grain formation is crucial to improve both the seed yields and NUE (Ma and Zheng, 2016).

As indicated above, a N source-placement study (Malhi et al., 2010), which included two sources of N (urea and controlled release urea; CRU) applied alone and in combination in a blend, placement methods [spring-banded (SB), fall-banded (FB), or split application (half of fertilizer spring-banded and half broadcasted at tillering)], produced an overall positive, but marginal impact on NUE in canola, when spring-banded urea was used as the control in our analysis. Their results showed that fall-applied CRU produced the lowest NUE (19.4 kg kg^{-1} N), whereas spring-banded CRU produced the highest (24.5 kg kg^{-1} N) NUE, with a narrow range. In general, irrespective of the difference in N source, spring-applied N treatments had higher NUE than that of the fall-applied CRU. This may be due to volatilization, demineralizing or leaching of CRU under warm fall conditions or early spring weather conditions. However, the authors have concluded that for boreal soils of the Canadian prairies, spring-banded CRU is as effective as urea, and in some years more effective, in increasing crop yield and N recovery. Split applications of urea can also be effective and have an advantage in minimizing the risk of N losses.

3.1.3 Water supply vs. nitrogen use efficiency

The canola crop root system has a high surface area characterized by long root hairs, which play an important role in nutrient acquisition and transport in water-limited soils (Pan et al., 2016). For instance, dry spring conditions can leave soil N ‘stranded’ due to impaired root growth, thus restricting available N uptake (Pan et al., 2007). Previous studies showed that water supply during the flowering period is critical for oilseed production as low soil moisture content during this crop growth stage can negatively impact plant N uptake, thus reducing photosynthetic activity of leaves and mobilization of the assimilate (Morrison and Stewart, 2002; Gan et al., 2004, 2008). Another study showed that with increasing available water and fertilization, spring canola becomes more efficient in accumulating both grain mass per unit grain N and grain N per unit of available N supply (NUE) (Maaz et al., 2016). In addition, NUE components analysis indicated that water-enhanced yields were correlated with higher N uptake and utilization efficiencies, which in turn were attributed to higher grain N utilization efficiency, followed by higher N retention. Most canola production occurs in arid and semi-arid regions where irrigation infrastructure is absent, therefore, canola cultivars should be screened for improving WUE and grain N accumulation in environments with limited water supply (Maaz et al., 2016).

Except for one study conducted by Smith et al. (2019), the NUE studies that we considered in our analysis did not include irrigation treatment, where the water deficit conditions would be minimized. However, in some studies, stubble management treatments were included in combination with N rate with the objective of conserving available soil water to support the crop productivity and improve the N use efficiency. No positive impact on NUE was reported in the studies that were considered, and soil water deficit conditions may have played an important role in the mediocre response to N treatments.

3.1.4 Genotypic variation vs. nitrogen use efficiency

Genotypic variation in NUE has been reported among canola cultivars, which suggests that uptake and distribution of N in canola are inherited traits. Significant genotypic variations in yield under N limiting conditions and in yield responses to high inputs of fertilizer N were reported for spring canola. Furthermore, it was indicated that the genotypic differences in NUtE are more apparent under limited N than under optimum N supply. The yield response of canola cultivars under limited N level may depend partially on their inherent ability to remobilize N from senescing leaves and translocate them to developing seeds (Svecnjak and Rengel, 2006). In addition, the extensiveness of the canola root system correlates with genotypic variation in NUE

(Maaz et al., 2016). A previous study reported that the NUpE of canola seed is predominantly determined by root growth instead of the N uptake rate per unit of root surface (Kamh et al., 2005). Several studies have indicated the genetic diversity of N-related traits in both spring and winter cultivars under field and controlled conditions (Svečnjak and Rengel, 2005; Kessel et al., 2012; Ulas et al., 2013; Lee et al., 2015). Combining the genetic diversity of the spring and winter gene pools using backcrosses may enhance genetic variation for NUE improvement (Bouchet et al., 2016). Moreover, genetic variation in the activity of different nitrate and ammonium transporters could be relevant to improve NUpE in canola (Xu et al., 2012).

3.2.1 Sulphur use efficiency of canola

Canola is sensitive to S concentrations in plant tissue, as S is an essential component of the amino acids, cysteine and methionine, and oilseed crops in the Brassicaceae family contain high levels of sulphur- containing secondary metabolites, called glucosinolates. Canola requires about 4 times more S than that of wheat or maize, and an adequate supply of S is important for optimum growth and yield (Abdallah et al., 2010). In canola, a low S supply suppresses the development of reproductive organs and leads to silique abortion, decreased seed yield, and decreased oil content (Ngezimana and Agenbag, 2014). Therefore, oilseed crops have a particularly great demand for S compared to cereal crops (Haneklaus et al., 2007). Field trials carried out over the years across the Canadian prairies determined that in canola, optimum yield can be achieved at rates of application of 15-30 kg S ha^{-1} (Malhi and Gill, 2006, 2007; Karamanos et al., 2007; Malhi et al., 2007a).

Both N and S are important constituents of protein and adequate supplies of both nutrients are required to optimize crop yield (Grant et al., 2012). Inadequate S combined with an excessive amount of N can lead to a nutrient imbalance that can restrict protein synthesis and reduce canola growth and yield (Malhi and Gill, 2002, 2007). The interactive effects of N and S on canola yields have demonstrated that N fertilizers stimulate plant S uptake and yield responses to applied S only occurred when N was applied (Ngezimana and Agenbag, 2014). Therefore, N and S additions must be in balance for optimum crop yield and it is suggested that in Canadian prairies S to be applied in a compound fertilizer having N: S ratio of 5:1 to 7:1. Field crops in eastern Canada are rarely fertilized with S as anthropogenic sources of S from airborne pollution (acid rain) and inherent soil S reserves are sufficient to meet crop S requirements (Ma et al., 2019).

Sulphur application can also influence canola quality. Under S deficient conditions, the concentration of oil in canola increased with S application (Grant et al., 2012). In addition, the application of S with N on S deficient soil has been reported to increase seed protein content (Malhi, 2006; Malhi and Gill, 2007; Egesel et al., 2009). In contrast, some studies reported a reduction in protein content with S application which can be attributed to dilution from increased seed yield response when a severe S deficiency was corrected (Malhi and Gill, 2002; Grant et al., 2003a).

3.2.1 Occurrence of sulfur deficiency

In many areas where canola is grown, S deficiencies can be noted (Grant et al., 2012). In Canada, most canola crops are grown in the parkland region of the three prairie provinces (Statistics Canada, 2011) and more than four million ha of agricultural soils in those regions are deficient or potentially deficient in plant available S for high seed yield of canola (Grant et al., 2012). Sulfur deficiency is greatly affected by soil characteristics. On soils that are low in organic matter, S release by mineralization is limited and on coarse-textured soils, S has leached out from the rooting zone over time (Franzen and Grant, 2008). The risk of S deficiency decreases with higher organic matter content and higher potential mineralization as sulphate is released slowly from organic matter through mineralization. In Canada, S deficiencies were identified on the Gray Luvisolic soils, because they are highly leached soils with a low organic matter content. Sulphur deficiencies have been identified on a broad range of soils in North America with the increased production of canola, use of higher yielding cultivars, movement to more intensive crop production systems and decrease in aerial deposition of S due to increased air quality standards. Application of S fertilizer to canola crops is recommended due to a decrease in seed yield under S deficiency (Grant et al., 2012).

3.2.2 Sulfur fertilizer source, and timing and method of application

Various S-containing fertilizers are utilized, including gypsum ($CaSO_4 \cdot 2H_2O$) and potassium sulfate (K_2SO4), but in the northern great plains most widely used S sources are ammonium sulfate $(NH_4)_2SO_4$), ammonium thiosulfate $(NH_4)_2S_2O_3$) and various elemental S forms. Before S can be utilized by the plant, it must be converted to SO_4- S (SO_4) ions as plants absorb S primarily through the roots from the soil solution in the form of ($SO_4^=$) (Grant et al., 2012). Ammonium sulfate, gypsum, and potassium sulfate supply S in the SO_4 form, while the S_2O_3 in ammonium thiosulfate rapidly oxidizes to plant available SO_4. Ammonium sulfate does not require time for oxidation as it provides S in the form of $SO_4^=$. Therefore, applications can be made in both spring and fall due to fertilizer being available for crop uptake upon dissolution and movement into the soil solution in the rooting zone. (Malhi, 1998; 2005; Grant et al., 2004). However, autumn applications can cause leaching losses under high moisture conditions in sandy soils thereby reducing fertilizer use efficiency (Malhi, 1998; 2005; Grant et al., 2004; Malhi et al., 2009).

Elemental S fertilizers must be oxidized to sulfate before they are available for crop uptake and the oxidation is mediated by soil microorganisms. However, in many environments the oxidation rate of S is generally not rapid enough to release sufficient available S to optimize yields of Brassica species in the year of application, or possibly for several years. In general, the soils on the semi-arid Canadian prairies do not reach temperatures above 10 ºC until mid May and microbial involvement of S oxidation may be slow due unfavourable soil conditions particularly cool temperatures resulting in reduced availability of SO4-S to the respective crops (Malhi and Leach, 2003; Wen et al., 2003; Grant et al., 2004; Karamanos and Poisson, 2004). This may explain the poor or negative response to elemental S by the canola crop. Therefore, elemental S should be managed in a manner that increases particle dispersion and contact with the soil microorganisms to accelerate the oxidation process (Grant et al., 2012). Recent work with micronized elemental sulfur shows promise for canola (Bremer et al., 2021).

Canola has a high demand for S during flowering and seed set (Malhi et al., 2007b). If deficiencies occur during the growing season, application of S source as late as rosette to early bolting can be beneficial. However, seed yield will generally be lower than if S had been available from the start of crop growth (Grant et al., 2012). In addition, ammonium sulfate and ammonium thiosulphate may have residual benefits on S availability for several years after application, depending on the environmental conditions. For example, in the Canadian prairies under low leaching conditions, applications of 20–30 kg S ha^{-1} as ammonium sulphate reduced S deficiency in crops for 2-4 years after application (Grant et al., 2003b, 2004; Malhi and Leach, 2003; Karamanos and Poisson, 2004). Residual benefits from sulfate fertilizers may be due to carry over of $SO_4^{=}$- S as ammonium sulphate has been shown to enhance soil $SO_4^{=}$- S (Malhi et al., 2009).

Under adequate soil moisture conditions, a range of application methods can be used to supply readily available S for plant growth and the response to the method of placement for S source varies with the soil and weather conditions. In a previous study conducted in the black and gray soils of the northern Canadian prairies, similar canola yields were obtained by applying ammonium sulphate as a surface broadcast, in-soil banded or seed-placed, under reduced or conventional tillage (Grant et al., 2004). However, a three-year study conducted in northern Saskatchewan reported a higher seed yield with placement of ammonium sulphate in the seed row and/or side-banded compared to broadcast and incorporated S in one year, while in the remaining two years all treatments had comparable yields (Malhi and Gill, 2002). This may have occurred because under drier conditions the S bands were better accessed by the roots compared to the shallow placement in surface soil.

3.2.3 Genotypic variation on sulfur use efficiency

Most of the canola currently produced is from hybrid cultivars as it has a higher yield potential compared to open pollinated cultivars (Carew and Smith, 2006). Previous studies conducted across western Canada indicated that, hybrid cultivars produced higher yields at a given S level than did open pollinated cultivars (Karamanos et al., 2005; Brandt et al., 2007). Despite the yield differential, the optimum yield can be achieved with S levels similar to those required to achieve sub-optimal yield of open-pollinated cultivars, showing that the hybrid cultivars may be better able than the open-pollinated cultivars to extract S from the soil (Karamanos et al., 2005; 2007; Malhi and Gill, 2006).

3.2.4 Effect of field management practices on sulfur use efficiency

Our analysis shows that adjusting N rate with S rate the highest SUE (30.2%) as compared to other management practices, such as S rate, timing by source by S rate, timing-growth stage by S rate (Fig.2). The N rate by S rate study was conducted in eastern Canada, where soil moisture was not as limiting a factor as in the Canadian prairies. This multiple year (2012-2014) study comprised of 12 treatment combinations with three levels of S (0, 20 and 40 kg ha-1) and four levels of N (50, 100, 150 and 200 kg ha-1) rates. Results showed that the growing season had a significant effect on the SUE of different treatments (Ma et al., 2020). These results indicate that the effect on SUE among years was not consistent when applied N rates were considered, however, it confirmed that the highest SUE rate corresponded with no or low applied S applied. It appears that the available soil S content for canola in eastern Canada has been sufficient for satisfactory production of canola. The lowest SUE was noted from a three-year (2000-2002) study that included two rates of S (20 and 40 kg S ha–1) applied in fall or spring using elemental S and sulphate-S as sources. Results suggested that, S applied in the sulphate form produced higher SUE, as compared to those of the treatments with elemental S in all years (Malhi and Leach, 2003).

3.2.5 Meta-analysis of factors affecting NUE and SUE

For the current meta-analysis, we have included 730 pairwise comparisons of agronomic management practices and genetic assessment studies. The agronomic studies included N rate, canola species by N rate, N rate by S rate, S rate and timing by source by S rate. Overall, the results of our analysis show that the addition of N and S fertilizer across North America had a negative impact on NUE and SUE as compared to corresponding controls (Figs. 2 and 3), but in most cases, the treatment effects on seed yields were positive with a diminishing trend (data not shown). The negative impact for NUE ranged from -39.0% to - 25.8% with a mean value of -32.4%, whereas for SUE it ranged from -9.8% to - 35.8% with a mean value of -22.8%. Some of the effects on NUE and SUE were statistically significant ($P < 0.05$). Among them, only the N rate by S rate resulted in a significant increase in SUE (30%). Furthermore, almost all the agronomic management practices used for increasing yield resulted in a negative impact on NUE. Studies that looked at the method of application (N source-placement) showed a positive, but marginal effect with a 7.5% increment. The timing by N rate management practice resulted in the greatest negative impact with a -54.2 % (Fig.2). Maaz et al. (2016) reported that environmental conditions and cultural practices, such as weather, water availability, tillage practices, residue retention, crop rotation, and fertilizer rate, timing, placement, and N source are the most influential factors that affect NUE in crop production systems.

3.3 Phosphorous use efficiency of canola

Phosphorous is a macro-nutrient that plays a vital role in energy metabolism and it is a vital component in the plant including nucleic acids and phospholipids (Subedi and Ma, 2009; Plaxton and Lambers, 2015). Phosphorous deficiency is one of the major constraints that limits canola yield (Korkmaz and Altintas, 2016). Previous studies showed that dry matter accumulation and canola yields are responsive to P applications up to 60 kg P ha^{-1} based on soil P pools and are linked to soil P availability (Brennan and Bolland 2009). Appropriate P fertilization is critical in the early phase of canola for optimum seed yield. However, over-fertilization of P increases the risk of water pollution, leading to eutrophication. Therefore, improving phosphorous use efficiency (PUE) is important for the economic production of canola and sustaining environmental quality (Korkmaz and Altintas, 2016).

The PUE is the amount of total biomass, or yield, that is produced per unit of P absorbed (Veneklaas et al., 2012). PUE depends on soil type, genotypic differences, and P application rates. Improving the efficiency of P fertilizer use for crop growth requires enhanced P acquisition efficiency from the soil and enhanced utilization of P in processes that lead to accelerated growth and greater allocation of biomass to the harvestable parts (Veneklaas et al., 2012). Phosphorus efficient plants can produce high yield under low soil P conditions. In canola, P accumulation peaked at mid silique-filling, with the majority of P accumulated during the post-flowering stage (Rose et al., 2009). Canola requires more P to optimize yield than grain cereal crops. However, it requires low P application due to the high efficiency of canola in scavenging both soil P and applied P (Brennan and Bolland, 2009). The fertilizer P requirements for profitable yields were generally obtained by varying P addition, separately or combined with different N rates, to determine P accumulation and seed yield responses (Ma and Zheng, 2016). Previous studies indicated that NH_4 based fertilizers largely stimulate P uptake in canola and higher seed yields and effectiveness of P fertilizers could be achieved when P applied with NH_4-N sources (Brennan and Bolland, 2007; 2009). Furthermore, a recent study conducted in Ontario showed that, under adequate soil P supply conditions, P uptake in canola was largely enhanced by N additions, especially at higher rates of N (Ma and Zheng, 2016).

3.4 Improving water use efficiency (WUE) of canola

Canola is a somewhat drought tolerant crop with a deep taproot system, and it can extract water from a soil depth down to 1.7 m (Din et al., 2011; Zhu et al., 2016). Out of total soil water extraction, canola can withdraw 45% of water from below 0.6 m (0.6 -1.7 m) depth. In addition, the water requirement for canola is less compared to other field crops such as corn (*Zea mays*), sorghum (*Sorghum bicolor*), and cotton (*Gossypium hirsutum* L.). Also, when canola is grown in a short growing season the irrigation requirement is further reduced (Katuwal et al., 2020).

Oilseed yield is expected to increase with water use, up to a maximum yield potential (Anastasi et al., 2010). The rate of yield increase, relative to increased water use, represents a measure of water productivity. Crop water productivity also known as WUE refers to a given level of biomass or seed yield per unit of water used by the crop (Hatfield et al., 2001). WUE depends on inherent crop productivity, growing condition (photoperiod and effects of atmospheric temperature and humidity), and harvest index (Aiken and Lamm, 2011). Water utilization of a crop is primarily affected by its canopy and weather conditions under adequate soil water supply

(Suyker and Verma, 2010). These effects are represented by seasonal crop coefficients and the potential evaporative demand (ETp) of the atmosphere. The crop coefficient refers to the fraction of potential evapotranspiration (ET) which the crop is expected to use on a given day. The crop coefficient value varies with the crop stage (Aiken and Lamm, 2011).

One of the greatest challenges for agriculture is to develop technology or agronomic options to improve WUE. Water use efficiency is partially a function of canola adaptation to environmental conditions. Therefore, favourable agronomic managements are of great importance. Canola has been shown to have WUE, from 8.3 to 11.4 kg ha^{-1} mm^{-1} in the sub humid regions of Canada (Faraji et al., 2009). The growing season on the Canadian prairies generally extends from May to August with most of the precipitation during June and July. After seeding, canola emerges, normally in May, then grows rapidly through June and early July. The rapid increase in leaf surface area, along with high air temperature can create a moisture deficit during the growing season. This deficit moisture condition can arise depending on the amount of spring soil moisture and the local level of precipitation and under limited soil moisture, crop seed yield can be harmed due to water stress at later stages of development (Bullock et al. 2010). In addition, canola prefers cooler temperatures, especially during the flowering period. Therefore, high temperatures during the flowering stage can lead to a reduction in yield (Cardillo et al., 2014).

Aiken and Lamm (2011), stated that delaying initial irrigation can reduce evaporation from the soil surface before canopy closure and increase the crop transpiration fraction of ET. The canopy of the spring canola is established under cool conditions with modest evaporative demand; therefore, it can avoid evaporative losses. Water use efficiency of spring canola can be enhanced by minimizing evaporative losses from soil by delaying initial irrigation, seeking rapid canopy closure, or earlier planting which forms the canopy under conditions of low evaporative demand. In addition, increasing harvest index can improve WUE and it can be favoured by planting optimal populations, selecting appropriate planting dates, cultivars, or hybrids, and avoiding water deficits for vigorous growth and during floral development and seed fill. Furthermore, developing varieties and hybrids, which maintain crop productivity and yield under soil water deficit conditions can increase WUE. Deficit irrigation is a method of utilizing limited irrigation water resources, in which crops are supplied with water below their evapotranspiration requirements during less critical growth stages (Yang et al., 2017). A previous study conducted in the U.S. Southern Great Plains showed that, adopting spring canola cultivar L140P and skipping irrigation during the vegetative stage (seeding to bolting) can enhance WUE in water limited semi-arid regions like the U.S. Southern Great Plains (Katuwal et al., 2020).

The second most effective practice for improving WUE was maintaining stubble height of the crop preceding the canola crop through growing season. This research consisted of leaving wheat stubble standing at various heights including extra tall (45 cm), tall (30 cm) and short (15 cm) heights from the soil surface. The effect of the stubble height on WUE was compared with that of no stubble. Generally, compared with cultivated stubble, extra tall stubble (45 cm) had the highest WUE followed by tall (30 cm) and short (15 cm) standing stubble (Cutforth et al., 2011). The treatment with no stubble had the lowest WUE. Cardillo et al. (2015) reported that depending on stubble height, stubble management changed the microclimate near the soil surface by reducing wind speed, solar radiation, and soil temperature throughout the life cycle of canola. Tall stubble was found to reduce wind speed, soil drying, and evapotranspiration compared to shorter stubble. Tall stubble may have increased seed yield and WUE by providing a favourable micro-climate for increased water conservation.

The third most effective practice for improving WUE was the time of stubble management, which included stubble maintained at 30 cm in fall and seeded in spring, stubble maintained at 15 cm in height and seeded in spring, stubble cut at 30 cm followed by cultivation in fall and seeded in spring, stubble cut at 30 cm and seeded with an extra 34 kg N ha^{-1} added in spring, stubble cut at 30 cm in fall and cut to 15 cm and seeded in spring and stubble cut at 30 cm tall in fall the cultivated in spring and seeded. Among these treatments stubble maintained at 30 cm with extra N produced the highest WUE compared to stubble cut at 30 cm tall in fall then cultivated in spring and seeded, suggesting that both soil moisture and added N had a synergistic positive effect on plant growth and yield resulting in an improved WUE (Cutforth et al., 2006). These results agree with those of Miller et al. (2003) and Cutforth et al. (2002), who reported that canola and mustard grown in the semi-arid prairie can respond to higher levels of N under favorable moisture conditions. The negative impact on WUE from the species by stubble management (fallow vs. stubble) was mainly due to poor yield response to any stubble by both *B. napus* and *B. campestris*, compared to fallow (Angadi et al., 2008).

3.4.1 Meta-analysis of factors affecting water use efficiency

Among nine management combinations, three management practices, namely irrigation by growth stage (48.5%), stubble height (11.4%) and time of stubble management practices (6.3%) had a significant positive impact on WUE whereas, the effects of irrigation rate (9%) and ability to irrigate (rainfed vs. irrigated) (3.6%) were positive but marginal (Fig.4). In contrast, the species by stubble management (-68.6%), species by seeding date (-26.8%) and species by water regime (-12.6%) practices had significantly lower effect on WUE. The combined effect of row spacing and different stubble height (-1.05%) was marginal but negative (Fig.4). The treatment effect of the irrigation by phenology (growth stage) on WUE was compared with that of dryland (rain-fed). Among these treatments' irrigation initiated at the emergence to harvest had the highest WUE followed by full season irrigation (seeding to harvest), whereas withholding irrigation at the reproductive stage resulted in the poorest WUE (Katuwal et al., 2020). These results confirm that a satisfactory supply of water at the reproductive stage of canola is key for improved WUE. As overall aboveground biomass and leaf area index reaches a peak during the reproductive stage (Katuwal et al., 2018), it likely increases total water loss through surface transpiration and increases evapotranspiration (ET) in canola. In addition to the increased ET requirement, the reproductive stage is characterized by many water sensitive processes such as floral retention, floral bud development into pods and assimilate supply from leaves and pods for seed setting which determines yield in oilseed crops (Eck et al., 1987; Sweeney et al., 2003; Katuwal et al., 2020). Katuwal et al. (2020) reported that skipping irrigation during the vegetative stages and irrigating only during the reproductive stage could maximize water productivity without significantly changing seed yield in canola.

In the Brown and Dark Brown soil zones, which comprise most of the semi-arid Northern Great Plains, the potential evaporative demand for water usually exceeds the water available to the crop, representing the greatest limitation to crop production in this semiarid region (Cutforth et al., 2002). Therefore, improving WUE, especially in the drier regions of the prairies, is an important consideration for increasing yield (Hu et al., 2015). In the present analysis the impact of several field management practices including seeding date, irrigation regime, farming technique, stubble type, stubble height, irrigation, or lack thereof, irrigation rate, and irrigation based on phenology, on the WUE of canola were considered. Overall, field management practices enhanced WUE by 4.5% (with a 95% confidence interval of -8.85 to 17.90%) compared to the respective controls.

4. Summary and conclusion

Economical and environmentally sustainable food production is vital to meet global demand as human population continues to increase. While genetic improvement for enhanced productivity of the world's most dominant food and fiber crops are in progress, the adoption of appropriate crop management practices to utilize production inputs, particularly N and water effectively, is becoming imperative for reaching the genetic potential and economic sustainability of those field crops.

A meta-analysis is a statistical method that can be used to comprehensively evaluate the effect of a given agronomic practice or genetic factor on a large scale and can help explain the causes of variations. Canola is the second largest field crop grown in Canada, and a significant and expanding oilseed crop in the Northern Great Plains and Pacific Northwest region in the U.S.A. No other meta-analyses were found for crop inputs on canola although one review by Assefa et al. (2018) summarized the major management factors determining the productivity of spring and winter canola in North America.

For our analysis, we collected 730 measurements associated with 'factors affecting water and plant nutrients- (N and S) use efficiency in canola' conducted in North America (Canada and U.S.A). The dataset consisted of 355 measurements for NUE from 12 peer-reviewed publications from 2008 to 2020, 276 measurements for SUE from 4 peer-reviewed publications from 2002 to 2020 and 99 measurements for WUE from 8 peer-reviewed publications from 2004 to 2020. The available data was used to performed meta-analysis, to assess the effect of different field management practices, such as nutrients (N and S) applications, as single or combined sources of the nutrient, irrigation, tillage and stubble management on the nitrogen, sulphur and water use efficiencies of canola. The objective was to understand the influence of field management practices on nutrients and water use efficiencies and to identify the suitable strategies to improve canola production in North America.

Overall, the results of our analysis show that the effects resulting from N and S fertilizer applications across North America negatively impacted NUE and SUE, when compared to corresponding controls. This was mainly due to the diminishing nature of productivity with an increasing rate of applied plant nutrients. Some of the effects on NUE and SUE were statistically significant at $P < 0.05$. All the field management practices assessed for NUE resulted in a negative impact, except for N placement and timing, where the effect was positive, but marginal. Timing by N rate studies produced the greatest negative impact on NUE.

Only the N rate by S rate fertilizer research showed a significant increase in SUE. Among nine management combinations, three management practices, namely irrigation by growth stage, stubble height and time of stubble management practices had a significant positive impact on WUE, and the effects of irrigation were positive but marginal. In contrast, the species by stubble management, species by seeding date and species by water regime practices had a negative effect on WUE. The effect of combining row spacing with stubble height was negative, but marginal. Among these treatments, irrigation maintained at reproductive development to physiological maturity had the greatest WUE followed by full season irrigation (seeding to harvest), whereas withholding irrigation during the reproductive stage resulted in the poorest WUE. These results confirm that adequate soil moisture during the reproductive stage is crucial for improved WUE in canola.

The lack of positive impacts on NUE in canola for applied N combined with other management practices may be a result of confounding effects, such canola genotypes (cultivars) with a higher response to applied N under varying growing conditions, initial available N content of soils, fluctuation of soil moisture conditions during the growing season in each production region, and sufficient availability of other plant nutrients, such as P and S for satisfactory growth and development. The use of higher rate of N under poor moisture conditions, could create an adverse growing environment for the crop (additive or synergistic effect of salinity and drought), lowering both the productivity and NUE. The positive, but marginal effect of the split applied control-release N source (urea) on NUE in canola suggest that, for improved NUE, integrated management practices, including appropriate N source and method of application, need to be further evaluated. Furthermore, the use of S in SO_4 form in combination with appropriate N source may result in improved SUE in canola. As in most other field crops, satisfactory soil moisture is crucial for high yielding of canola. Therefore, for greater WUE, maintenance of adequate soil moisture conditions from flowering until physiological maturity through supplementary irrigation and/or maintaining stubble height is critical. Finally, there has been limited attention or focus on the assessment of canola species and cultivars for improved NUE, SUE and WUE. There is need for the new canola cultivars to be further evaluated on a regional basis for their nutrient and water use efficiencies to ensure economic sustainability for this crop in North America.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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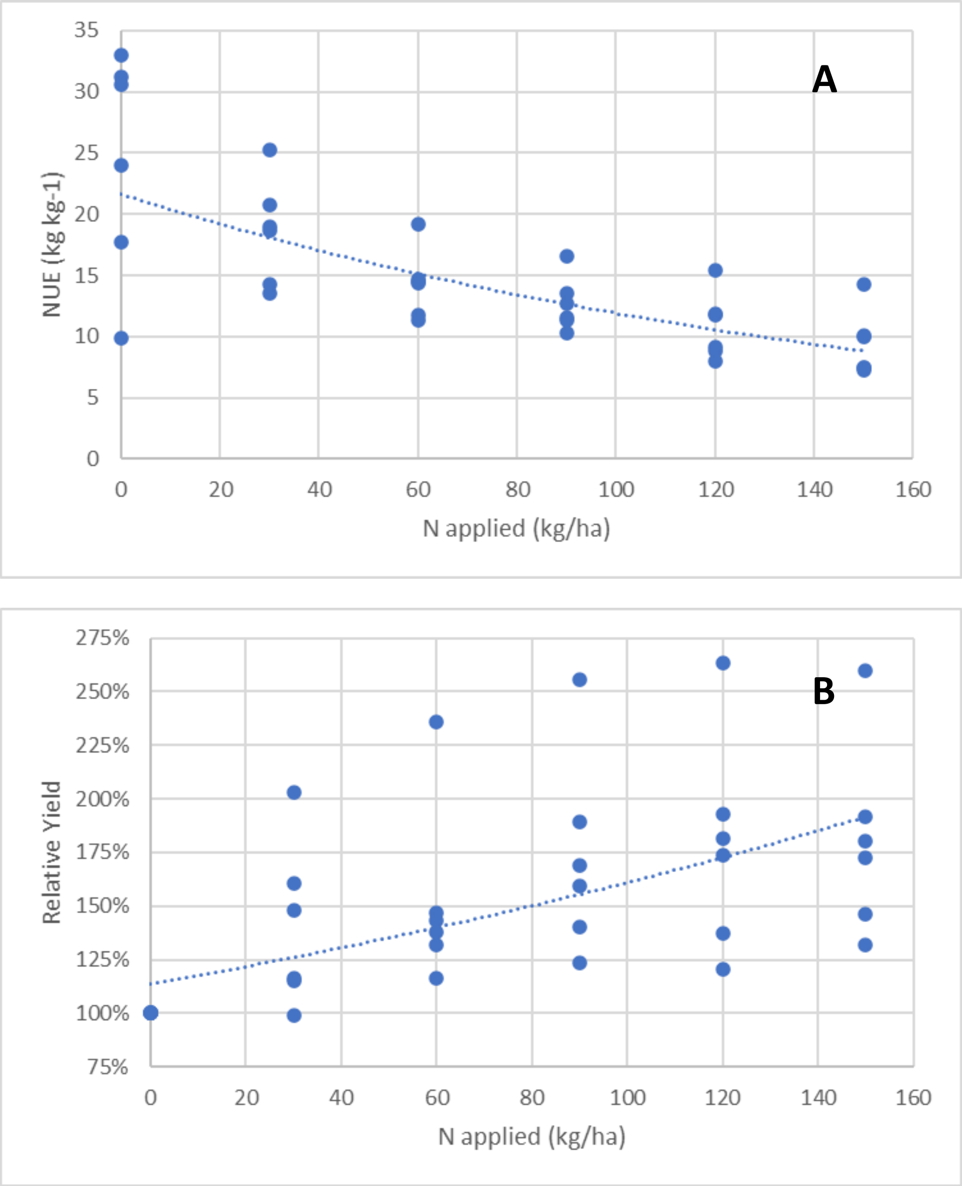

Figure 1. The effect of N applied to canola crops on (A) NUE and (B) yield relative to the control. Data for these figures were collected from Malhi et al. (2007).

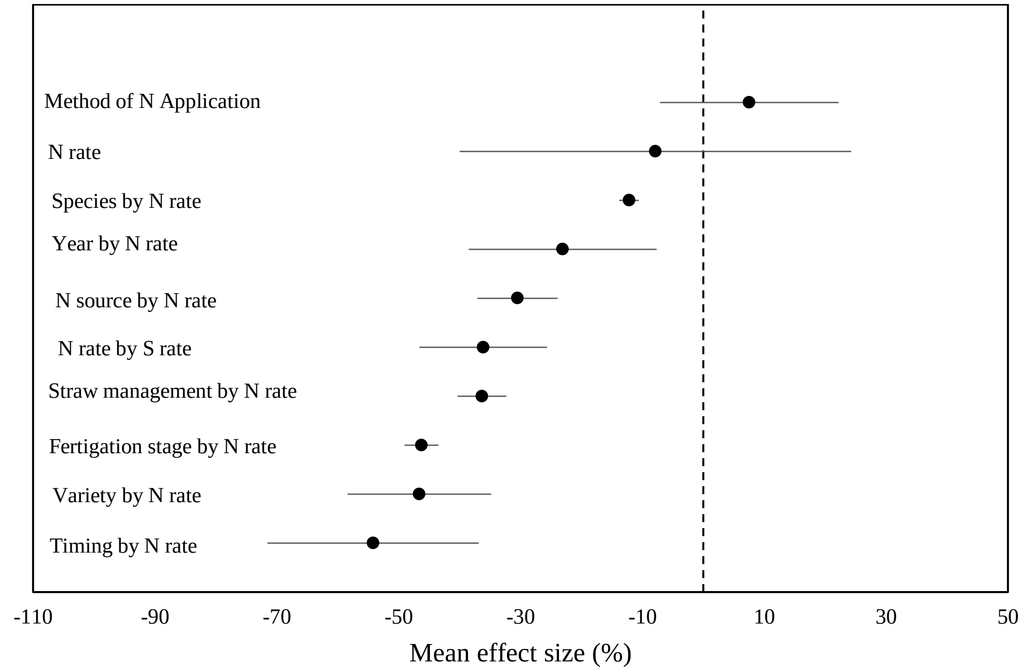

Fig. 2. Effect of different field management practices on nitrogen use efficiency (NUE). The error bar indicates the 95% confidence interval. When the error bar does not overlap with zero, the results from the treatment group are significantly different from that of the control group at P < 0.05.

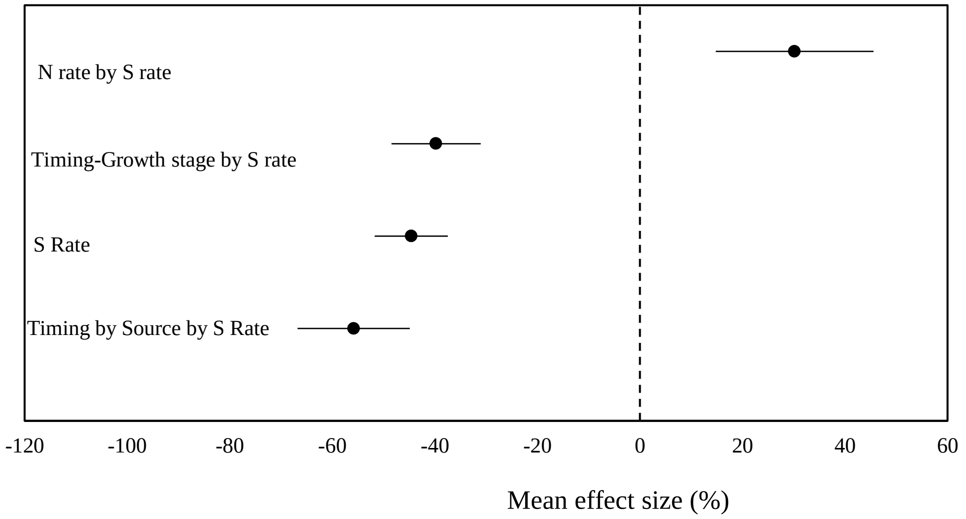

Fig. 3. Effect of different field management practices on sulphur use efficiency (SUE). The error bar indicates the 95% confidence interval. When the error bar does not overlap with zero, the results from the treatment group are significantly different from that of the control group at P < 0.05.

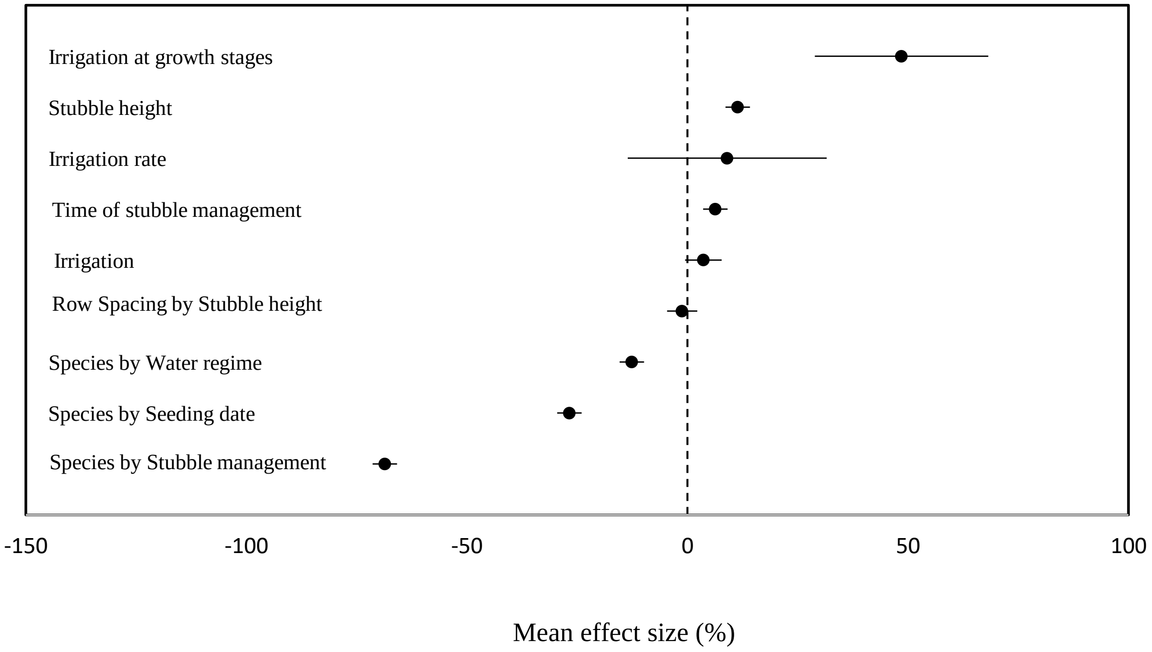

Fig. 4. Effect of different field management practices on water use efficiency (WUE). The error bar indicates the 95% confidence interval. When the error bar does not overlap with zero, the results from the treatment group are significantly different from that of the control group at $P < 0.05$.