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Environmental advantages and potential of faba bean (*Vicia faba L.*) cultivation in Norway, with a special focus on C and N inventory

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Abstract

Faba bean (*Vicia faba L.*) is a legume capable of BNF that has the potential to play a role in achieving climate goals while influencing the future of Norwegian agriculture. The GreenPlantFood project is exploring ways to improve sustainability of the farm to fork food system in Norway, and this thesis seeks to contribute both agronomic and plant residue information on faba bean grown in Norway. Faba bean is a high protein crop, and comparisons of food production in Norway have shown that faba bean production has 14-29 times lower GHG emissions per kg protein compared to dairy beef meat, and 9-15 times lower GHG emissions compared to milk. Faba bean also provides agronomic and environmental benefits in cultivation. Up to 200 kg N ha^{-1} N fertilizer can be saved in crops grown after faba bean, and grain yields respond positively to faba bean residue compared to other grain residue. BNF capabilities are thought to play a role in this, but the specific mechanisms behind these benefits are not completely understood. A collection of promising faba bean varieties were sown on two different dates (27 April, 14 May) at Vollebekk research farm in Ås. Two plots were sowed for each variety in both sowing times. A selection of 10 varieties from the 14 May sowing time were selected for full plant analysis. 0.5 m^2 subplots were used for each of the 10 selected varieties. Plants from each subplot were harvested, measured, and divided into seeds, stems, pods, and leaves for nitrogen and carbon analysis.

Yield data from the full plots showed very little statistically significant differences between varieties, but sowing time had a significant effect on dry seed weight ($p\text{-value} < 0.001$). Mean dry seed weight for plants sown 27 April (6.63 kg) was significantly higher than mean dry seed weight for plants sown 14 May (5.18 kg). The plants sown 27 April received 42.9 °C extra degree days, and 35.5 mm additional precipitation. Subplot plant analysis showed that seeds had 4.59% N, leaves had 2.40% N, pods had 1.37% N, and stems had 0.69% N. These N contents support previous findings regarding faba bean residue nitrogen content. Carbon contents of plant residue parts were all roughly 40%. Of the plant material included in post-harvest plant residue, only leaves had above the 2% nitrogen content threshold that is necessary for successful nitrogen mineralization. Harvest index and residue nitrogen content were negatively correlated (Pearson's r = - 0.776). High harvest index is important for the plant protein function of faba bean, and high residue nitrogen content is a valuable factor in faba bean's role in crop rotations.

Contents

Introduction

Human induced climate warming has adversely impacted environments and communities globally, and continued warming will put pressure on food production and access (IPCC, 2022). Unsustainable agricultural development and high impact diets contribute to food system vulnerability (IPCC, 2022). Global per capita meat consumption has doubled over the past 60 years (IPCC, 2019). Localized food systems, and increased legume production have both been highlighted as valuable tools for mitigating negative climate effects (IPCC, 2019). Meat and milk production are currently the two main sources of agricultural income in Norway (Knutsen, 2020). The Norwegian government though, has stated that it will reduce emissions 50% by 2030, and notes that immediate shifts in the agricultural sector are necessary to achieve this goal (Norsk-Regjeringen, 2020).

Faba bean (*Vicia faba L.*) is an important legume that can contribute to mitigation of negative climate effects through various ecological services (Köpke & Nemecek, 2010). A meta-analysis of LCA studies conducted by Clune et al. (2017) demonstrated that global warming potential (GWP) for legume production is low compared to GWP for meat production. Norwegians currently eat more meat than is recommended by the government, and even a small shift towards plant proteins could have significant environmental benefits (Svanes et al., 2020).

In Norway, faba bean has shown potential as an important plant protein source (Abrahamsen et al., 2019). Its high protein content can be a valuable tool as Norwegian diets increasingly include plant proteins (Abrahamsen & Waalen, 2020). Legume crops like faba bean have been underutilized in economically developed regions, and a reliance on legume imports is an environmental burden (Mayer Labba et al., 2021). Expanding domestic legume production could significantly decrease soybean meal imports for Nordic countries (Abrahamsen et al., 2019, Peltonen-Sainio et al., 2013). Most available plant protein products in Norway are currently made with imported materials (Abrahamsen & Waalen, 2020). Following field trials in 2000, faba bean production began to grow in Norway and has continued to rise through present growing seasons (Abrahamsen & Waalen, 2020, Stabbetorp, 2020). Crop rotations that combine legumes with cereals can lessen numerous environmental pressures (Tidåker, 2021), and improve yield for both faba bean and the other crop in rotation (Angus et al., 2015, Stagnari et al., 2017).

The extent to which faba bean can influence Norwegian agriculture, and the best way to agronomically utilize faba bean are still unknown. These uncertainties are the basis for this thesis which is a part of the Norges forskningsråd (Norwegian research council) project GreenPlantFood (319049), a continuation of the FoodProFuture project. The goal of the GreenPlantFood project is to contribute to restructuring the farm to fork food systems in Norway towards a more sustainable and green value chain. This project is a direct contribution to the goals laid out by the Norwegian government pertaining to future emissions and agricultural production. This thesis contributes to WP 5 of the project which focuses on the agronomic potential and opportunities for Norwegian crops to increase the production of plant protein, and to future LCA framework through full crop residue analysis.

Literature Review

Faba Bean General Information

Faba bean (Vicia faba L.), also referred to as fava bean, field bean, broad bean, or horse bean, is an important grain legume crop globally and was one of the first ever domesticated crops, with cultivation dating back to early Neiolithic times when agriculture was first developing (Duc, 1997, Kirk, 2004). The species has great genetic diversity with more than 38,000 germplasms identified and conserved globally (Duc et al., 2010). Legumes were first brought to European fields in the 10th century and are thought to have played a role in improving general nourishment through soil quality benefits (Vasconcelos et al., 2020). Over the past 100 years, legumes have developed a relationship as an old-fashioned food that cannot return the same yield as cereals and contains numerous antinutritional compounds (Vasconcelos et al., 2020). Ecological, ethical, and health concerns regarding the current level of animal meat production have led to a developing interest in the role legumes can play in future food production (Vasconcelos et al., 2020). While many warm season legumes such as soy, cowpea, drybean, peanut, and pigeon pea have increased in acreage recently, faba is one of several temperately grown legumes that has experienced a decrease in global acreage (Stagnari et al., 2017). Faba bean growing acreage decreased from over 5 million ha in the early 1960's to around 2.5 million ha in the early 2000's (FAO, 2022). During this time, faba bean acreage in China decreased from about 3.5 million ha to 1.25 million ha (FAO, 2022). This decrease was the largest factor in the overall drop in growing area. Productivity, though, has increased. Global faba bean production has increased by about 40% from 1985 to 2017, despite a loss of almost 1 million ha (FAO, 2022).

Morphological and Botanical Information

Faba bean is a temperate annual legume with a hollow erect stem that can reach 2 meters high (Bilalis et al., 2003, Smither-Kopperl, 2019). The stem grows indeterminately and develops nodes with a leaf and an axillary raceme flower cluster (Duc, 1997). The leaves develop anywhere from 2 to 8 leaflets, with the leaflet quantity per leaf increasing higher up on the plant (Duc, 1997, Kirk, 2004).

Flowers express papilionaceous structure and are roughly 2 to 3 cm long (Duc, 1997, Kirk, 2004). Faba bean flowers appear as white, with a brown or violet blotch on the petals (Kirk, 2004). Flowering time is a critical factor in successful suitability of faba bean to its local environment (Patrick & Stoddard, 2010). Faba bean plants grown in a Nordic cultivation study reached flowering after 650 degree days (0°C base temperature) (Bodner et al., 2018). A study in Norway by Sørheim (2021) showed that the variety Vertigo flowered 594 degree days after sowing (0°C base temperature). Faba bean plants require pollinating insects for both self and cross-pollinating plants, and in the absence of pollination can undergo self-fertilization which is linked with lower yields (Gasim & Abdelmula, 2018).

Pods produced by faba bean plants are typically smooth and green during development and upon maturity, change color to dark brown or black (Smither-Kopperl, 2019). As many as twelve seeds can develop in one pod (Duc, 1997, Smither-Kopperl, 2019), but the average is much lower and is greatly dependent on genetics, biotic, and abiotic factors (Li & Yang, 2014). Pod size can even vary greatly across a single plant (Li & Yang, 2014). Faba bean generally produces large seeds, and like the seed number, the size is highly variable (Abrahamsen et al., 2018, Patrick & Stoddard, 2010). While smaller seeds are generally cheaper to purchase and easier to sow, seed size is strongly positively correlated with yield (Abrahamsen & Waalen, 2020, Duc, 1997). The seeds can vary in color as well, and the flavonoid composition of the seed coat determines the appearance (Nozzolillo et al., 1989).

Faba bean possesses a shallow root system that rarely exceeds one meter in length (Manschadi et al., 1998). Root depth, like most legume crops, is generally around 10 times shallower than cereal crops (Gregory, 1988). Taproot depth by cultivar is strongly influenced by the agroclimatic location (Zhao et al., 2018). Faba beans cultivated in areas with low water availability, or plants exposed to drought stress, tend to possess roots that spread wider and deeper in the soil (Manschadi et al., 1998, Smither-Kopperl, 2019, Zhao et al., 2018). Both the taproot and the lateral roots are able to develop N fixing nodules (Duc, 1997). Sørheim (2021) found that nodule density is much higher in the uppermost 5cm of the roots. That same study on Norwegian grown faba bean showed that nodulation is most abundant at the early flowering and flowering stage, and that nodules first develop roughly three weeks after sowing (Sørheim, 2021). Faba bean roots can also form endomycorrhizal symbioses, though not as commonly as the rhizobial symbiosis (Duc, 1997). The day length consideration of faba bean depends on the location of cultivation, and northern European cultivated faba bean expresses an inclination towards long day conditions (Bodner et al., 2018).

Nitrogen Importance

Nitrogen (N) is a necessary building block for all living organisms, and is the nutrient of greatest concern for agricultural production (Raza et al., 2020). Nitrous oxide (N_2O) is a greenhouse gas 300 times as potent as CO_2, and is a byproduct of N fertilization in agricultural production (Tian et al., 2020). Agricultural practices are the largest factor in anthropogenic N_2O emissions, and N fertilization emits 1 kg N_2O for every 100 kg applied (Stagnari et al., 2017). Plants do not have the ability to utilize atmospheric N (Butler et al., 2016), but in the early 1900s, this inability was circumvented through developments in chemistry, and the first synthetic N fertilizer producing plant was developed in Germany in 1912 (Morrison & Morrison, 2001). Synthetic N fertilizer is produced through the Haber Boschz process (Butler et al., 2016, Raza et al., 2020). This process uses fossil fuels to fix atmospheric N with hydrogen to produce ammonia (NH_3) and is a highly energy intensive process as it requires high temperature and pressure (Raza et al., 2020).

Biological Nitrogen Fixation

Members of the Fabaceae family form symbioses with diazotrophic bacteria which have the ability to fix atmospheric N to NH_3 (Dupont et al., 2012, Vasconcelos et al., 2020). The process, biological nitrogen fixation (BNF), plays a critical role in agronomical and ecological processes (Dupont et al., 2012). A majority of N that builds biological systems is fixed through BNF (Rípodas et al., 2014).The NH_3 produced through BNF can then be converted into the building blocks for proteins and genetic material (Vasconcelos et al., 2020). N fixation is an energy intensive process and requires ATP and electrons from the plant (Raza et al., 2020). Rhizobia use the energy provided by the plant to break the double bond in atmospheric dinitrogen (N_2) (Vasconcelos et al., 2020). At least 16 ATP are needed for the nitrogenase enzyme to break the N_2 double bond, and reduce one molecule of N_2 (Vasconcelos et al., 2020). Different fabaceae members have specific symbioses with certain rhizobacteria (Geurts & Bisseling, 2002). *Rhizobium leguminosarum* bv. *Vicae* is an inoculum that can be used to enhance faba bean BNF if natural populations are not present (Elsheikh & Elzidany, 1997, Smither-Kopperl, 2019). These preexisting rhizobia populations are more prevalent in traditional faba cultivation areas because the rhizobia are already present (Karkanis et al., 2018). Outside of Norway, inoculated treatments have shown the ability to significantly improve faba bean N yield up to 40 kg N ha^{-1} (Elsheikh & Elzidany, 1997). The benefit from inoculation in the study by Elsheikh & Elzidany (1997) was similar to that from fertilizer addition on both the seed and N yield. Research in Norway by Sørheim (2021), though, suggests that inoculation and starter fertilization are not necessary for faba bean cultivation in Norway.

Agronomics

Inclusion of faba bean in a crop rotation program is a valuable tool (Angus et al., 2015, Stagnari et al., 2017). Faba bean can be used effectively as a green manure for subsequent crops (He et al., 2020). The BNF properties of faba bean can improve the resulting soil N level, but inclusion of faba bean in a cropping system is also advantageous due to disruption of disease and weed pressure (Angus et al., 2015). The specific processes affecting improved growth in crops following faba bean cultivation are not fully understood (Senaratne & Hardarson, 1988).

Inclusion of legumes in crop systems can lower nitrous oxide emissions and create economically viable cropping systems that simultaneously benefit the environment (De Ron et al., 2017). It is reported that up to 100-200 kg N ha^{-1} of N fertilizer can be saved for the growth period of the crop following faba bean (Jensen et al., 2010). Based on the N_2O emissions estimation by Stagnari et al. (2017), this equates to 1-2 kg ha^{-1} less N_2O emitted due to faba bean cultivation the prior season. Potential N fertilizer savings may not be due to faba adding N to the soil, but instead due to lower N removal from the soil (Senaratne & Hardarson, 1988). These savings could be a major incentive in increased faba bean production though, as fertilizer prices have spiked in Norway recently (Waalen et al., 2022).

Faba bean is most suitable for rotation with cereals, and cereal yield can increase by 20% when intercropped with grain legumes in temperate environments (Stagnari et al., 2017). Grain yields were up to 33% higher when grown on faba bean residue compared to barley residue (Wright, 1990). Faba bean yield can also be improved by inclusion in a crop rotation (Angus et al., 2015). This mutualistic benefit is an important possibility in Norway due to the well-established cereal production in southeastern lowland areas where faba bean is most common (Knutsen, 2020).

The breakdown of N in the soil (mineralization) is a complicated process that is highly dependent on the composition of the plant material (Senaratne & Hardarson, 1988). Wright (1990) noted that differences in residue decomposition were responsible for faba bean's superiority as a green fertilizer compared to barley residue. Successful N mineralization requires a C:N ratio of 20 or lower (Kaul et al., 1996, Senaratne & Hardarson, 1988), It is common that C content is roughly 40% in leftover plant material, so therefore N content must be over 2% for successful N mineralization (Kaul et al., 1996). It is common that less than 25% of N in legume residues becomes available during the first two years of decomposition (Vallis, 1983). Temperatures around or below freezing can significantly slow N mineralization rates, but mineralization of plant material with a low C:N ratio is less affected by cold temperatures (Frøseth et al., 2022).

No-tillage agriculture is a soil health and energy saving practice that has been shown to achieve similar yields in grain crops (Phillips et al., 1980). A six year study in Italy by Alhajj Ali et al. (2018) found that a no-tillage system for faba bean growth achieved comparable yield, and 29% less fossil fuel use when compared to a conventional tillage system. Alhajj Ali et al. (2018) note though, that adoption of no-tillage cultivation is often accompanied by a reliance on synthetic chemicals for weed control.

Legumes and Faba Bean in Norway

The Norwegian climate is conducive to meat, dairy, and seafood production, but high protein plants can play a significant role in the future (Svanes et al., 2020). Research in Norway has indicated that faba bean has GHG emissions per kg protein 14-29 times lower than dairy beef meat, and 9-15 times lower than milk (Svanes et al., 2020). The Norwegian consumers are increasingly aware of this and interest in plant protein products has risen (Abrahamsen & Waalen, 2020). There is high potential to increase the quantity of plant protein produced in Norway by utilizing the existing grain acreage (Abrahamsen et al., 2019). There was more legume production in Norway in 2020 (48,000 daa) than either 2018 (32,000 daa) or 2019 (28,000 daa) (Grieu et al., 2021).

Faba bean production has increased from 300 daa in 2011 to 25,000 daa in 2021, largely due to increased access to early varieties (Waalen et al., 2022). Late varieties have dominated the Norwegian faba bean market, but recent developments to early varieties have made their cultivation increasingly popular (Grieu et al., 2021). In 2019, late variety Vertigo, accounted for over 40% of the faba bean growing area in Norway, and roughly 32% in 2020 (Abrahamsen & Waalen, 2020, Grieu et al., 2021). Cultivation area of early varieties such as Louhi and Sampo quadrupled from 2019 to 2020, and in 2020 early varieties accounted for 37% of the Norwegian cultivation area (Grieu et al., 2021). The continued development of early varieties is an important factor in expanding the faba bean cultivation area in Norway (Abrahamsen & Waalen, 2020).

Health and Dietary Aspects

The potential health benefits of increased faba bean production and consumption are impressive and numerous (Crépon et al., 2010, Karkanis et al., 2018). Mediterranean and middle eastern communities have utilized faba bean as a dietary staple for millennia (Crépon et al., 2010). High protein content, low fat content and a plethora of antioxidants and other beneficial compounds make grain legumes useful aspects of a diet (Mayer Labba et al., 2021). Protein content in faba bean seeds can range from 17-35% (Karkanis et al., 2018, Mayer Labba et al., 2021). Globulins make up the largest portion of the proteins in faba bean (Warsame et al., 2020). Faba bean seeds are a particularly valuable source of the amino acids, arginine, lysine, and leucine (Karkanis et al., 2018). Faba bean seeds, like most grain legumes are low in methionine, cysteine, and tryptophan (Karkanis et al., 2018). The grain legume amino acid composition is complimentary to that of cereal grains (Mayer Labba et al., 2021). This complimentary relationship makes faba bean and other grain legumes a valuable tool in combination with cereal grains in fulfilling the full spectrum of amino acids in diets that involve less meat (Mayer Labba et al., 2021).

Iron and Zinc are minerals of concern in the construction of plant-based diets, and there is large variation in the levels of these nutrients across different faba bean varieties (Mayer Labba et al., 2021). Faba bean can also act as a functional food due to the presence of the beneficial L-DOPA (Verni et al., 2019). This amino acid is a converted to dopamine and supports dopamine levels in the brain. L-DOPA is used in drugs designed to treat parkinsons disease (Karkanis et al., 2018).

While faba bean consumption poses many benefits, there are also antinutritional compounds that must be considered in both production for human, and animal consumption (Crépon et al., 2010). Faba contains high levels of vicine and convicine, pyrimidine glycosides that act as precursors of aglycones divicine and isouramil, two main factors in favism (Rizzello et al., 2016). Individuals with a glucose-6-phosphate dehydrogenase (G6PD) deficiency (favism) can experience dangerous acute hemolysis because of faba bean consumption (Rizzello et al., 2016). It is common that individuals who suffer G6PD deficiency are not aware of their condition (Crépon et al., 2010). As a component in animal feed, vicine/convicine, and tannins have all been shown to negatively affect monogastric animals (Crépon et al., 2010). Seeds without tannins have improved protein digestibility and energy value when used as feed for pigs and poultry (Crépon et al., 2010). Another antinutritional compound commonly found in faba bean seeds is lipoxygenase (Warsame et al., 2020). Lipoxygensases are considered antinutritional because they create undesirable flavors following lipid oxidation during food processing (Warsame et al., 2020).

Stresses

Abiotic Stresses

The two major abiotic stresses for faba beans grown in Europe are drought and heat (Karkanis et al., 2018). A study on faba bean grown in nordic conditions showed that high temperature during the flowering stage was the most detrimental factor to yield (Bodner et al., 2018). High summer temperatures, and specifically warm night temperatures, significantly decreased yield in the study by Bodner et al. (2018). Frost damage in the reproductive stages of faba bean is a serious concern in colder climates (Karkanis et al., 2018). As faba bean reaches maturity it is sensitive to cold temperature (Abrahamsen et al., 2018). Freezing tolerance is an important factor in winter hardiness (Duc, 1997), and across varieties tested in Norway there is a wide range in level of frost tolerance (Abrahamsen et al., 2018).

While drought is an important factor in some agroclimatic regions, waterlogging during flowering poses an equally damaging threat to faba bean development (Karkanis et al., 2018). Faba bean can tolerate waterlogging better than other legumes, but still experiences significantly increasing seed yield loss as waterlogging length increases (Pampana et al., 2016). After 5 days of waterlogging, even though faba bean plants appear visibly unaffected, plant mass at maturity and seed yield are both negatively affected (Pampana et al., 2016). Waterlogging hinders BNF and N mobilization causing a decrease in photosynthesis and therefore the ability to thoroughly develop seeds (Pampana et al., 2016).

Soil pH is an important factor in successful growth and development of faba bean plants (Abd-Alla et al., 2014, Belachew & Stoddard, 2017). Faba bean mass accumulation, nodulation, and N fixation were negatively affected by alkaline soils in a study by Abd-Alla et al. (2014). A soil pH of 8 or higher negatively affects nitrogenase activity and leghaemoglobin content in faba bean root nodules (Abd-Alla et al., 2014). Soil acidity can also negatively affect root and nodule development (Belachew & Stoddard, 2017, Schubert et al., 1990). Both nodule quantity and quality were decreased by lowering pH, while root length and thickness also decreased in acidic stress conditions (Belachew & Stoddard, 2017). According to Schubert et al. (1990), Faba bean plants grown in pH 4.7 and 5.4 fixed less N than those grown in pH 6.2 and 7.0. The response of faba bean development to soil pH is highly dependent on the specific rhizobium symbioses (Kinraide & Sweeney, 2003).

Biotic Stresses

Weeds have been reported to reduce faba bean yields up to 50 percent, and it is important weed removal is conducted early (25-75 days) to ensure a high yield (Frenda et al., 2013, Tawaha & Turk, 2001). Faba bean though is very competitive against weeds compared to other legumes because of its height and strong initial development (Frenda et al., 2013).

Fungal infection is a serious concern when growing faba bean in all growing regions (Torres et al., 2006). Ascochyta blight (Ascochyta fabae), chocolate spot (Botrytis fabae), and rust (Uromyces vicae-fabae) are the three main fungi that affect faba bean globally (Maalouf et al., 2019, Torres et al., 2006). All these fungi can cause yield loss of over 30 percent for faba bean (Karkanis et al., 2018, Maalouf et al., 2019), and chocolate spot can inflict up to 61 percent yield loss (Woldemariam et al., 2008). Chocolate spot often develops toward the end of the growing season in Norway (Abrahamsen & Waalen, 2020).

Faba bean is also susceptible to faba bean necrotic yellow virus (FBNYV), and yellow bean mosaic virus (BYMV) (Elsheikh & Osman, 1995). Faba bean plants infected by virus show reduced yield, nodulation, N fixation, and total dry mass when compared to uninfected plants (Elsheikh & Osman, 1995). Faba bean affected by FBNYV can suffer up to 90% yield loss, and in certain areas this is the virus of highest concern (Maalouf et al., 2019). BYMV infection can decrease both seed protein content and yield in faba bean by significantly impacting important developmental stages such as flowering (Babiker et al., 1995). BNF is an important tool for faba bean to fight these viruses (Babiker et al., 1995, Elsheikh & Osman, 1995). Inoculation with suitable rhizobium strains can mitigate the negative effects of the viruses (Elsheikh & Osman, 1995), and N fertilization can negate the influence that BYMV has on seed protein content (Babiker et al., 1995).

Black bean aphid is a common pest, preying on young and developing leaves (Stoddard et al., 2010). These aphids can be controlled with foliar insecticides, but parasitoid control of aphids is also a useful tool in insect management (Hansen et al., 2008). A potential risk associated with aphid presence is the transmission of seed borne viruses through sap inoculation (Elsheikh & Osman, 1995).

Breeding

Faba bean is a genetically diverse crop with more than 38,000 germplasms conserved across the world (Duc et al., 2010). The main issue facing breeders is the yield instability of faba bean (Duc, 1997). The large diversity of faba bean, though, presents the opportunity to increase and stabilize yield (Maalouf et al., 2019). Breeding techniques have improved with developing molecular technologies (Maalouf et al., 2019). Breeding for tolerance against acidity and high ion presence is possible through early-stage resistance identification in tissue culture growth medium (Belachew & Stoddard, 2017). Both nutritional (proteins, antioxidants, minerals), and antinutritional (vicine, convicine) compounds vary greatly across cultivars, creating opportunities for breeding of more nutritious seeds (Mayer Labba et al., 2021).

Harvest and Processing

Ideal moisture content for faba bean seeds at harvest is around 15% (Jilani et al., 2012). It is important to harvest each variety at the appropriate time (Karkanis et al., 2016). After faba bean begins to ripen in the autumn, seed moisture content falls by just under 1% each day (Abrahamsen & Waalen, 2020). High moisture content in faba bean seeds can lead to higher emissions due to longer drying time (Korsæth & Hjelkrem, 2016).

Dehulling is a critical process in preparation of faba bean seed, and can can increase protein content while decreasing tannin content (Alonso et al., 2000). Mayer Labba et al. (2021) reported faba bean seed protein contents ranging from 26.2% to 32.8% across 15 varieties grown in Sweden. The primary use of faba bean in Norway is as concentrate, and there has been expressed interest from the concentrate industry in increased faba bean production (Abrahamsen & Waalen, 2020). It is possible to achieve high protein concentration through energy efficient dry separation for faba bean seeds due to low lipid levels (Heusala et al., 2020). Research conducted at Nofima (Norwegian food research institute) showed that faba bean fractions can contain 60% protein (Abrahamsen et al., 2019). Optimizing the fine fraction processing can achieve protein contents of up to 69.4% (Ertesvåg, 2020). Faba bean concentrate production has roughly 80-90% lower carbon footprint compared to dairy proteins when analyzed per kg protein (Heusala et al., 2020).

LCA

Life Cycle Assessment (LCA) is a tool to measure the environmental effects related to all steps of a product's life cycle. The measurement begins with the production or extraction of the raw materials used and runs through the eventual use of the product (Muralikrishna & Manickam, 2017). The specific methodology behind how to conduct a LCA is not well defined and is continuously evolving (Svanes, 2019). Even miniscule variations in the methodology used can lead to difficulty in comparing LCA studies. Raw data, however, from these studies can be an important aspect in building a library of data for future studies (Svanes, 2019).

Materials and methods

Plant material

The plant material was provided through the GreenPlantFood project, and the plants were grown at Vollebekk research farm in Ås as a continuation of previous faba bean trials at the site. Seeds were sown on two separate dates. The first sowing time was 27 April 2021, and the second sowing time was 14 May 2021. Seeds were sown roughly 4-5 cm deep, and each 8 m row was separated by a width of 12.5 cm. The sowing density was 60 seeds $m^{2\ -1}$. There were two replications of each variety within both sowing times.

10 varieties in the field sown on May 14 were selected for whole plant analysis. Within the full plot for each selected variety, there were two parts of a subplot that were combined in analysis of the data. The two subplot parts were measured on opposite corners of the main plot and were placed roughly three rows of plants in from each edge to help prevent an edge effect. The two halves of each subplot were 1 meter long and included two rows of plants. Each half of the subplot was determined to extend half of the width outwards of the two rows of plants for a total width of 25 cm. Each sublot half was therefore 0.25 m^2 and the collected subplot data for each variety was for an area of 0.5 m^2.

Soil sampling was conducted on 14 June 2021. Samples were taken from 6 different areas around the fields in Vollebekk with a standard soil sampling auger. The samples were sent to Jord og Vannlab (soil and water laboratory) at Jordfagbygget, NMBU, Ås. Samples were mashed with a mortar and pestle and sieved through approximately 0.8 mm sieve. The samples were stored in a freezer and then thawed and dried at 30-40 °C for approximately 26 hours. The samples were then analyzed for dry matter content, organic matter content, N content, carbon content, pH, potassium (K) amount, and phosphorus (P) amount.

Canopeo canopy measurements

Canopy coverage measurements were taken with Canopeo for IOS. Canopeo is a fractional green canopy cover diagnostic tool developed in Matlab at Oklahoma State University (Patrignani & Ochsner, 2015). The IOS app uses a picture of the canopy to estimate canopy coverage as a percentage of the area in the picture. Color ratios of red to green, blue to green, and excess green are used to classify all the pixels in the image into a binary image. In this final image, pixels that meet the canopy criteria of green are shown as white, and pixels that do not satisfy the green criteria are shown as black. The percentage of white pixels is the canopy cover measurement output (Patrignani & Ochsner, 2015).

Two canopy measurements were taken in each plot, and the average of those two measurements was used in analysis. All images were taken from approximately 140 cm high, and the two images were taken from opposite ends of the plot. Canopy measurements were recorded on plants in the 14 May sowing time on 16 June 2021.

Leaf collection

To account for leaf abscission throughout the season, leaves were collected from the plot area during the growth period. Leaves were collected from the ground or removed from the plant if they appeared to be desiccated or close to falling off. After leaves have fallen to the ground, they are quickly broken down and indistinguishable from the soil and therefore hard to include in measurements. The collected leaves were placed in labeled bags and dried in a Termaks TS4115 fan assisted drying chamber at 30°C. Leaf collection occurred on three dates, 30 July, 1 August, and 11 August 2021. These leaves were included in the final measurement for leaf dry weight combined with the collected leaves at harvest.

Harvest

The ten subplots from the 14 May sowing time were harvested from 7 September – 10 September 2021, 116-119 days after sowing. Vire, Louhi, and Vertigo were harvested on 7 September 2021, 116 days after sowing. Tiffany, Stella, Birgit, and Sampo were harvested on 8 September 2021, 117 days after sowing. Victus, Bolivia, and Daisy were harvested 10 September 2021, 119 days after harvest. All subplot harvesting and measuring was done by hand, so all ten plots could not be harvested in one day. Each plant in a subplot was cut at the base of the stem, and the entire above ground plant material was harvested. All plants for each variety were placed in a bag together and taken back to the Vollebekk barn for measuring, sorting, and storage. The length of each stem was measured from the cut base of the plant to the highest point on the stem. Following the individual plant length measurements, the plants in each plot were combined and the remaining measurements were taken for the whole variety. All seeds were counted by hand, and fresh seed weight was recorded with either Mettler Toledo PM4000 or Sartorius L220P balance. The plant material was sorted into stems, seeds, leaves (including leaves collected during growing period), and pods (**Figure 1**).

Figure 1. Stems, seeds, pods, and leaves separated into categories before drying.

Next, all samples were placed in bags (**Figure 2**) and moved to a Termaks TS4115 drying chamber for drying at 30°C. Seeds, leaves, and pods were stored in paper bags, and stems were stored in mesh bags. Samples dried at different speeds due to variety in the composition of the plant material. Samples were observed daily until they were deemed fully dried, and then they were measured for their dry weights with the same balances used for fresh weight. All dried plant material was then stored in the Vollebekk barn until milling occurred.

The full plots from the 27 April sowing time were harvested 9 September 2021, 135 days after sowing, and the full plots from the 14 May sowing time were harvested on 15 September 2021, 124 days after sowing. These full plots were harvested in a plot wise manner with a Zürn 130 plot combine harvester and analyzed the same day for fresh seed weight. Seeds were dried at 25°C and then dry weight was recorded in the same manner as the other weight measurements.

Figure 2. Seeds, stems, leaves, and pods bagged after harvest before drying and storage.

N, C, S testing

All aboveground collected plant residue was tested for N content. Both the Kheldal digestion procedure and the Dumas combustion procedure were used due to difficulties milling the plant material. Leaves and pods were milled to a uniform fine powder with a Foss Tecator Cyclotec 1093 sample mill. Both stems and seeds could not be milled as fine as the leaves and pods due to their rougher composition. The Dumas procedure requires a fine and uniform powder for analysis (Muñoz-Huerta et al., 2013). The stems and seeds were ground using Stein M-2 Sample Mill and a subset of each stem sample was sifted with a Endecotts 840-micron sieve. to produce a sample fine and uniform enough for the Dumas procedure. The seeds were just analyzed with the Kjeldahl method. All milled plant material was sent to LabTek analysis laboratory run by Biovit at NMBU for analysis. The Kjeldahl digestion procedure only measures the NH_3 content but can be used for samples that are not as finely milled (Muñoz-Huerta et al., 2013). Plant material analyzed with the Dumas procedure was analyzed for N, C, and S contents, while plant material analyzed with the Kjeldahl procedure was only analyzed for N content.

Calculations

Each of the sublots was 0.25 m^2, making the total area in each subplot 0.5 m^2. This area determination was used to calculate per hectare (ha) and per decare (daa) measurements.

Harvest index (HI) is the ratio of dried seed to aboveground plant mass. HI was calculated based only on the subplots as the above ground plant biomass is required.

N residue calculations were done using the N content percentage from the laboratory analysis and extrapolating the percentage from that sample to the whole dried plant mass for that subplot. Each plant category (seeds, stems, leaves, pods) was calculated individually. There were two samples of milled stems analyzed. The N contents from the finely ground sample analyzed with the Dumas procedure and the rougher sample analyzed with the Kjeldahl procedure were averaged to assume the stem N content. This is not a perfect estimation, and even though the Dumas procedure is a more holistic measurement because it includes nitrate (NO_3^-), the material sifted through the sieve cannot be assumed as an accurate representation of the entire stem. Certain compounds within the stem could have milled to a finer powder than others, and for this reason, an average of the two measurements was used.

Statistics

All statistical analysis was conducted using Jamovi, a statistical analysis application based on the R programming language. Correlation analysis was conducted with Pearson correlation test and the r value listed is the Pearson correlation coefficient. Dry seed weight (DSW) data from both sowing times was analyzed with Welch's One-Way ANOVA test and analyzed post hoc with Games-Howell Post Hoc test. These tests were used for both DSW across varieties, and DSW across sowing time, and were chosen because Levene's homogeneity of variances test failed (**Table A6**, **Table A11**). Seed moisture content was analyzed alongside DSW in the ANOVA test across sowing times. An ANOVA test of DSW for the four varieties from the two sowing times that tested both variety and sowing time as fixed factors failed both Levene's homogeneity of variances test (p-value <0.001), and Shapiro-Wilk normality test (p-value = 0.013) **(Table A 10**).

Weather

Weather data is from Norsk Klimaservicesenter which is run by Meteorologisk Institut. The weather station in Ås (SN17850) was used for temperature and precipitation estimates. Degree days were calculated as the cumulative amount that each day's average temperature was over the base temperature (0°C). Total rainfall was calculated as the sum of rainfall across the growing period. Days to harvest did not include the day of harvest as plants would not receive a significant degree day effect due to morning harvesting.

Results

Weather and precipitation

During the subplots' growth period, the temperature did not fall below 3.5°C between sowing and harvest, so there were not issues with frost. There was a total of 164.6 mm precipitation before harvest. This was the same for all three subplot harvesting days as there was no rain during the harvest period. After 116 days on 7 September, the degree day sum was 1848.9. After 118 days, on 9 September, the degree day sum was 1865.3, and after 119 days on 10 September, the degree day sum was 1901.7. The rain at the end of July lead to the leaf collection on 30 July, 1 August, and 11 August. The rain caused large amounts of leaves falling to the ground, and they would soon be indistinguishable from soil and dead weeds.

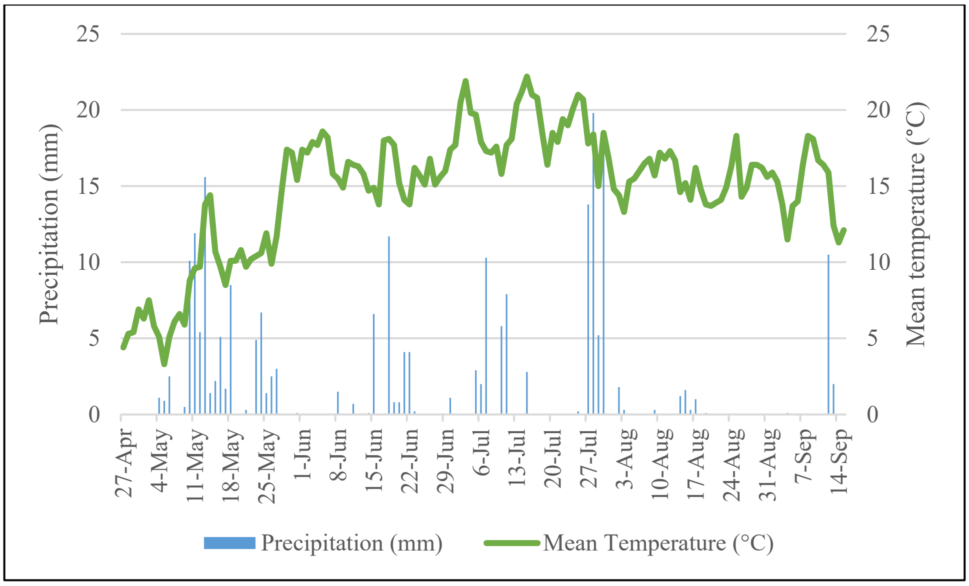


Figure 3. Precipitation (mm) and average temperature (°C) in Ås, Norway from the first sowing time (27 April) to the final harvest (15 September).

Comparisons of the two sowing times focus on the full plot harvests. Plants sown on 27 April were harvested 136 days later after accumulating 2017.3 °C degree days and receiving 212.6 mm precipitation. Plants sown on 14 May were harvested 124 days later after accumulating 1974.4 °C degree days and receiving 177.1 mm precipitation (**Table 1**).

Table 1. Harvest date, days to harvest, degree days (C), and total precipitation (mm) for both sowing times (27 April, 14 May).

Sowing date	27-Apr	14-May
Harvest date	10-Sep	15-Sep
Days to harvest	136	124
Degree days (°C)	2017.3	1974.4
Total Precipitation (mm)	212.6	177.1

Soil Samples

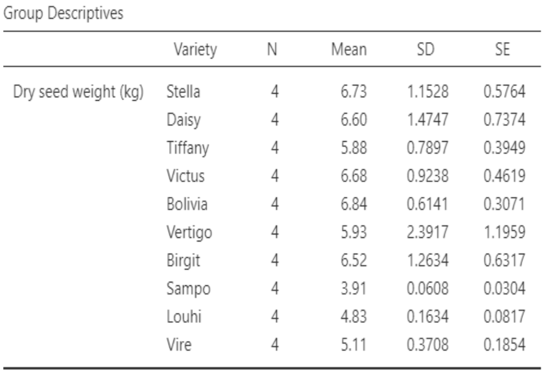
Mean SOM % across the 6 samples at Vollebekk was 7.89%. This is a standard SOM content for soils in the southeast of Norway, which have seen significant decline since the 1950's (Riley & Bakkegard, 2006). Mean soil pH of 6.32 is at a desirable level for optimal N fixation (Schubert et al., 1990). Mean C% and N% were 3.03% and 0.34% respectively (**Table 2**).

Table 2. Soil sample mean drymatter, SOM, total C%, total N%, and pH across 6 sample locations at the Vollebekk fields.

Drymatter %	SOM %	Tot. C %	Tot. N%	pH
98.16	7.89	3.03	0.34	6.32

Yield

Welch's One-Way ANOVA for full plot DSW for both sowing times showed that there were differences in the mean DSWs across varieties (p-value < 0.001) (**Table A7**). When analyzed with Games-Howell Post Hoc test for differences across the 10 varieties, very little was statistically significant (**Table A8**). Mean Bolivia DSW (6.84 kg) was significantly higher than mean DSW of both Sampo (3.91 kg) and Louhi (4.83 kg) (p-value = 0.018, and 0.045). Sampo mean DSW was also significantly higher than Louhi mean DSW (p-value = 0.006). These two varieties (Sampo, Louhi) had the lowest mean DSW. These two varieties also have the lowest standard error (SE) values out of the 10 varieties (**Figure 4**).



Group Descriptives

	Variety	N	Mean	SD	SE
Dry seed weight (kg)	Stella	4	6.73	1.1528	0.5764
	Daisy	4	6.60	1.4747	0.7374
	Tiffany	4	5.88	0.7897	0.3949
	Victus	4	6.68	0.9238	0.4619
	Bolivia	4	6.84	0.6141	0.3071
	Vertigo	4	5.93	2.3917	1.1959
	Birgit	4	6.52	1.2634	0.6317
	Sampo	4	3.91	0.0608	0.0304
	Louhi	4	4.83	0.1634	0.0817
	Vire	4	5.11	0.3708	0.1854

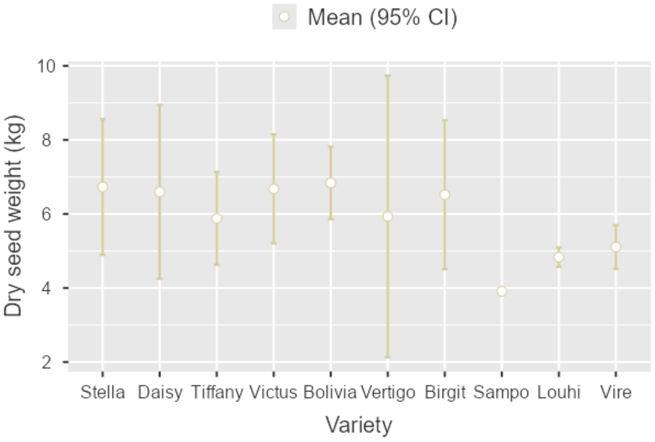


Figure 4. Group descriptives for mean dry seed weight (DSW) (kg) by variety, and 95% confidence intervals (p-value = 0.05) for each mean dry seed weight (DSW) (kg) by variety. Outputs from Jamovi.

Yield for the 10 subplots and the corresponding full plot yield for those plots in the 14 May sowing time was strongly correlated (Pearson's r = 0.892) (**Figure A3**). Moisture content for the 10 subplots and the corresponding full plots in the 14 May sowing time were also strongly correlated (Pearson’s r = 0.951) (**Figure A4**). Full plot DSW values shown in **Figure 5** are an average of two individual repetitions of each variety within the field used for the 14 May sowing time. Vertigo mean DSW was second lowest in the 14 May sowing time (**Figure 5**), but highest for the 27 April sowing time (**Figure A1**).

Sowing time had a significant effect on DSW (p-value < 0.001) (**Figure A5**. Correlation between harvest index (g g-1) and dry seed weight (DSW) (subplots) (g) with Pearson's r value.**Table A9**). Mean DSW for plants sown 27 April was 6.63 kg, significantly higher than mean DSW for plants sown 14 May was 5.18 kg (**Figure 6**). The plants in the 27 April sowing time received 42.9 °C extra degree days, and 35.5 mm additional precipitation. The earliest varieties Louhi, Sampo, and Vire had the lowest moisture contents at harvest for the subplots (**Figure 7**). Vertigo, a late variety, had a higher moisture content than any of the others, along with other late varieties (Birgit, Tiffany, Stella). Mean moisture content at harvest was almost twice as high for the full plots from the 14 May (18.7%) compared to the 27 April (9.56%) sowing time (**Figure A5**. Correlation between harvest index (g g-1) and dry seed weight (DSW) (subplots) (g) with Pearson's r value. **Table A9**).

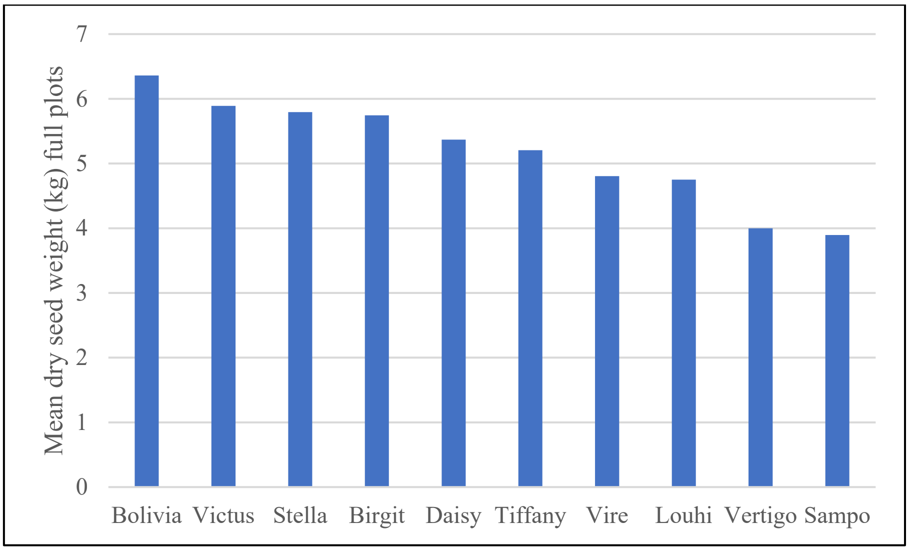


Figure 5. Mean full plot dry seed weight (DSW) (kg) of the 10 selected varieties from the 14 May sowing time.

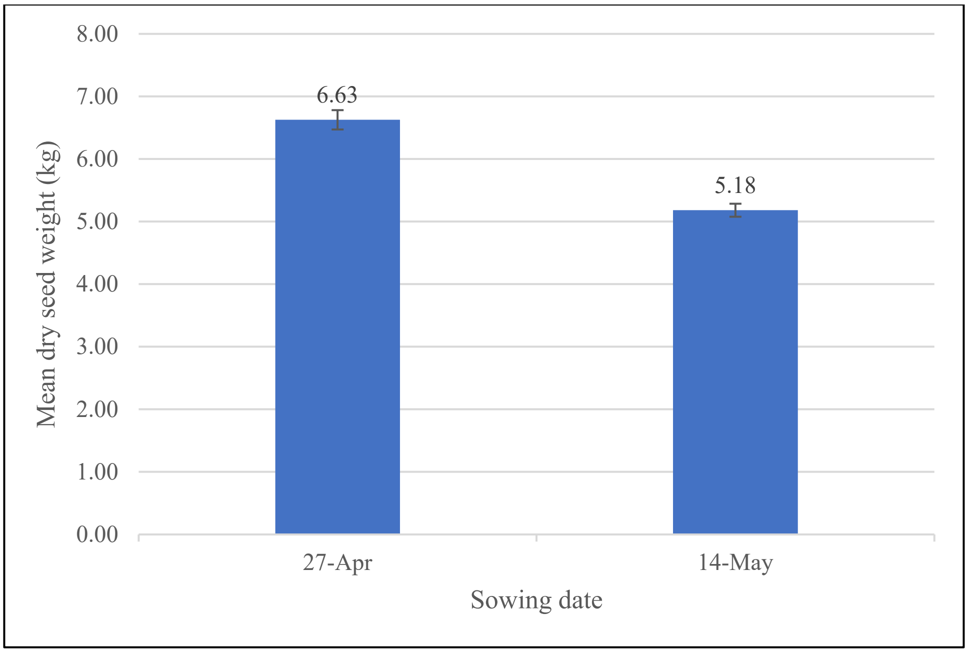


Figure 6. Mean dry seed weight (DSW) (kg) for the two sowing times (27 April, 14 May) with standard error bars.

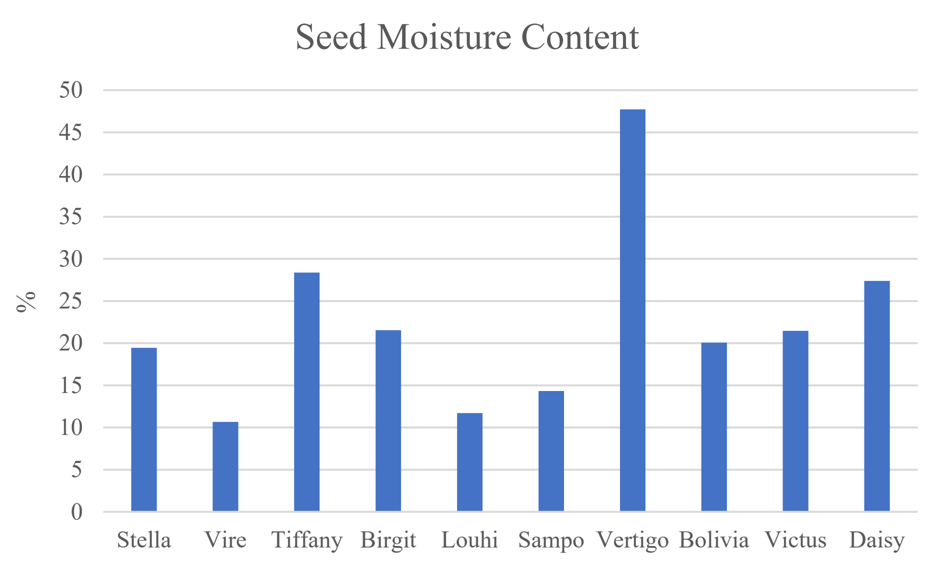


Figure 7. Seed moisture content as a percentage of fresh seed weight from the subplots harvested 7/10/22-10/10/22 from the 14 May sowing time.

Nitrogen analysis

Mean residue N content for the subplots was 3.58 g (**Table 3**). This is equivalent to 71.47 kg ha^{-1} (**Table 4**). Mean HI for the subplots was 0.49 g g^{-1} (**Table 3**). This HI value is in line with data from southern Germany that showed HI of 0.45-0.60 (Kaul et al., 1996). Mitiku & Assena (2015) found slightly lower HI values (0.35 to 0.45) in a study in Ethiopia. HI and residue N content were negatively correlated (Pearson's r = - 0.776) (**Figure 8**). The highest yielding variety from this study, Stella (360.91 g) had the second lowest residue N-content (3.25 g), and the highest HI (0.55). DSW and HI were not significantly correlated according to Pearson's correlation coefficient, but the statistic was relatively high and positive (r = 0.603, p-value = 0.065) (**Figure A5**).

Table 3. Dry seed weight (DSW) (g), harvest index (HI) (g/g), residue dry weight (g), and residue N-content (g) for subplots within 10 selected varieties with mean and standard deviation.

Variety	Plot	Dry seed weight (g)	Harvest index (g/g)	Residue dry weight (g)	Residue N-content (g)
Stella	2102	360.91	0.55	293.16	3.25
Vire	2106	285.65	0.52	266.19	3.16
Tiffany	2107	314.16	0.46	366.39	3.98
Birgit	2108	335.65	0.50	335.52	3.51
Louhi	2202	280.42	0.49	292.53	3.40
Sampo	2206	207.25	0.47	231.30	3.42
Vertigo	2207	259.39	0.44	332.25	4.00
Bolivia	2404	338.74	0.51	324.12	3.35
Victus	2502	324.93	0.49	342.18	3.92
Daisy	2602	311.37	0.48	340.80	3.76
Mean		**301.85**	**0.49**	**312.44**	**3.58**
SD		**42.71**	**0.03**	**38.93**	**0.31**

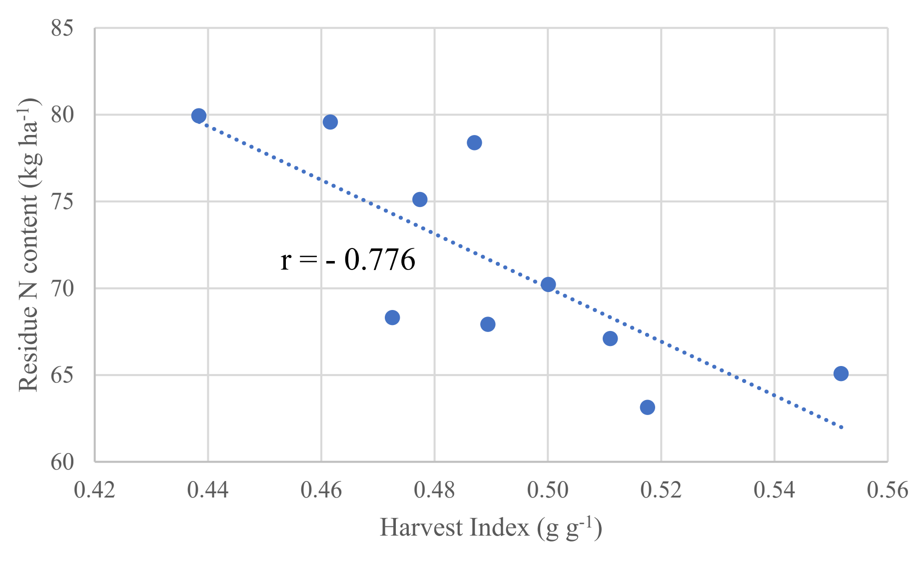


Figure 8. Correlation between residue N content (kg ha^{-1}), and harvest index (g g^{-1}) with Pearson's r value.

Mean N content varied across the different plant parts. Seeds had the highest mean N% (4.59%) out of any plant parts (**Table 5**). Leaves had the highest mean N% (2.40%) of residue plant material (stem, leaves, pods) (**Table 4**). Mean pods N% was 1.37% and mean stem N% was 0.69%. Kaul et al. (1996) reported pod N% of 1.6, and stem N% lower than 1%. This supports the findings of this study. The mean total plant residue N was 1.16%. Senaratne & Hardarson (1988) found that leftovers from faba bean (plant residue) harvested in Austria had 1.64% N.

Stem residue, leaf residue, and pod residue had similar C% with respective mean C% of 39.94%, 40.56%, and 41.12%. These mean C%'s support data that plants usually consist of 40% C (Kaul et al., 1996, Senaratne & Hardarson, 1988).

Canopeo canopy coverage mean measurements for the 14 May plants taken on 16 June (33 days after sowing) were strongly correlated with residue N content (kg ha^{-1}) (Pearson's r = 0.815) (**Figure 9**).

Table 4. Residue N content (kg ha^{-1}), mean stem N% (Dumas and Kjeldahl), leaves Dumas N%, pods Dumas N%, and combined plant residue N% for each variety with mean and standard deviation (SD).

Variety	Residue N content kg ha^{-1}	Mean stem N% (Dumas and Kjeldahl)	Leaves Dumas N%	Pods Dumas N%	Plant residue N%
Stella	65.08	0.65	2.20	1.30	1.11
Vire	63.13	0.90	2.20	1.20	1.19
Tiffany	79.57	0.65	2.50	1.30	1.09
Birgit	70.21	0.65	2.20	1.30	1.05
Louhi	67.92	0.75	2.40	1.10	1.16
Sampo	68.30	0.85	2.50	1.70	1.48
Vertigo	79.93	0.65	2.60	1.60	1.20
Bolivia	67.10	0.60	2.30	1.40	1.04
Victus	78.38	0.50	2.60	1.50	1.15
Daisy	75.11	0.65	2.50	1.30	1.10
Mean	**71.47**	**0.69**	**2.40**	**1.37**	**1.16**
SD	**5.93**	**0.11**	**0.15**	**0.17**	**0.12**

Table 5. Seed Kjeldahl N% by variety with mean N%.

Variety	Seed Kjeldahl-N%
Stella	4.4
Vire	4.6
Tiffany	4.5
Birgit	4.4
Louhi	5.1
Sampo	5.2
Vertigo	4.3
Bolivia	4.3
Victus	4.5
Daisy	4.6
Mean	4.59

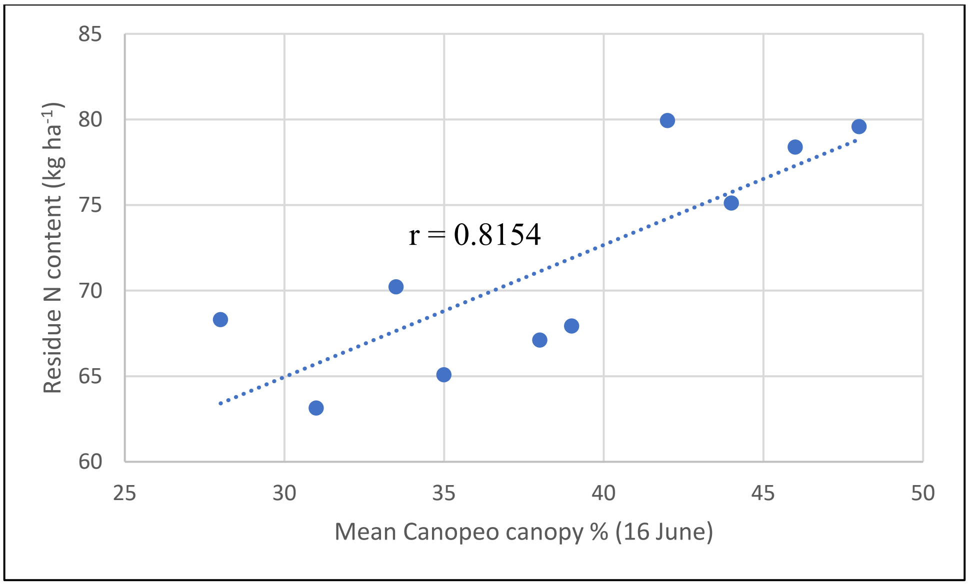


Figure 9. Correlation between residue N content (kg ha^{-1}) and mean Canopeo canopy % (16 June) with Pearson’s r value.

Discussion

It is difficult to make any statistical inferences about varietal influence on DSW values. DSW for the full plots from the 14 May sowing time had lower variance than for the combined sowing time DSW values. The two varietal repetitions within the 14 May sowing time, however, did not provide enough statistical power to make conclusions from that data. The combined data had very high variance within varieties likely because of the sowing time effect on DSW. It is hard to say whether the extra 42.9 °C degree days, and 35.5 mm of precipitation received by the plants sown 27 April was responsible for higher DSW and lower seed moisture content. Disease pressure could have also factored into these differences. For statistically significant comparisons of varieties in the future, more repetitions are likely needed within a single sowing time.

Mean SOM of 7.89% and pH of 6.32 are both indicative of soil suitable for faba bean production. Riley & Bakkegard (2006) predict through climatic modeling that soils in the southeast of Norway which currently have medium or high SOM will likely fall below 3% SOM, a proposed threshold for the sustenance of normal plant functions. The southeast of Norway, particularly the general Oslofjord area, is where Norwegian faba bean production has been focused to this point (Stabbetorp, 2020). The persistent use of inorganic N fertilizer can lower SOM mineralization rates by disrupting microbial activity in the soil (Mahal et al., 2019). The combination of these factors outlines the importance of agriculture that prioritizes soil health. It will be important to determine the extent that faba bean can mitigate some of the declining soil quality.

Data on N content in roots is hard to calculate due to difficulty handling fragile lateral roots, and the destructive nature of sampling (Gregory, 1988). A study on faba bean roots by Rowse & Barnes (1979) concluded that fragile lateral roots deep in the soil are critical to the root and plant function. Available data shows that the amount of N in legumes that is stored in the roots at harvest is usually less than 10% (Senaratne & Hardarson, 1988). This estimation of plant N allocation in roots applied to the collected data from this research adds no more than 8 kg N ha^{-1} to the total N residue.

Collected leaf litter was not analyzed separately from the rest of the leaves. Leaf litter collected during the growing season in a German study had a N content of 3.1% (Kaul et al., 1996). The same study estimated that up to 18kg N ha^{-1} leaf litter can fall from faba bean plants before harvest (Kaul et al., 1996). The mineralization of plant material is heavily reliant on its composition and therefore what type of residue it is (Senaratne & Hardarson, 1988). The residue C content of around 40% for the three residue groups measured indicates that N% from those residue groups must be around or above 2% for successful mineralization (Kaul et al., 1996). The mean N content of the leaves (2.40%) supports the idea that leaf litter falling throughout the growing season could contribute significantly to soil N content. The mean leaf residue C:N ratio is 16.9, below the proposed threshold of 20 (Senaratne & Hardarson, 1988). The rest of the plant residue material (stems, and pods) had N contents of 0.69%, and 1.37% respectively. These measures indicate that the stems and pods would not mineralize quickly due to high respective C:N ratios (57.88, and 30.01). It is therefore likely that leaves are contributing most to plant available N in the soil during the subsequent growing seasons. Despite mean leaf residue weight being much lower than mean stem residue weight (1,029.6 kg ha^{-1}, 3,531.26 kg ha^{-1}), the mean leaf N residue weight is still about the same as the mean stem N residue weight (24.87 kg N ha^{-1}, 23.56 kg N ha^{-1}). The N in the leaves made up about 35% of the total residue N, and it is likely that this content is largely responsible for the 25% of N in legume residue that Vallis (1983) claims becomes plant available during the subsequent year or two of decomposition.

Canopeo canopy coverage measurements on 16 June, just 33 days after harvest correlated strongly to the residue N content. Canopeo canopy cover measurements were not correlated with DSW from either the subplots (p-value = 0.340) or full plots (p-value = 0.455) (**Table A13**). This indicates that canopy coverage, and particularly the Canopeo app, is an effective tool to predict plant biomass, and residue N content, but not DSW.

The balance between HI and N residue is important in selecting which faba bean variety to grow. The inverse relationship between the two factors creates a breeding and variety selection conundrum. An increase in each factor provides a unique environmental service, but also a likely decrease in the unique environmental service of the other factor. Increasing HI adds to the efficiency of seed yield which helps faba bean contribute as a plant protein source in human and animal diets. Increasing N residue leads to a greater amount of green fertilizer that can potentially benefit subsequent cultivation. The relationship between DSW and HI has been discussed as positively correlated (Senaratne & Hardarson, 1988), and the statistics in this study are just outside the threshold for statistically significant conclusions. Perhaps more repetitions would strengthen the statistical confidence in the correlation.

Trials in Norway that analyze the inclusion of faba bean in crop rotations with different grain crops will be an important step towards understanding the benefit that faba bean and other legumes can have on Norwegian agriculture. Korsæth & Hjelkrem (2016) report that faba bean has a 27% lower climate warming potential than autumn wheat, and as discussed earlier, both faba bean and its partner in a crop rotation show yield improvements as a result of the rotation (Angus et al., 2015, Stagnari et al., 2017). The combination of reduced warming potential, and improved yield for both crops indicates a potentially significantly beneficial effect on emissions per unit of grain or faba produced. The extent of this benefit under Norwegian growing conditions is important to examine.

Increasing temperature and CO_2 concentration will both factor into the development of agriculture in Norway. The changing climate not only has negative effects on nature and people, but also impacts agriculture in ways that involve several entangled factors. Elevated CO_2 levels have been linked to increased yield, N fixation, total biomass, and HI in legumes (Parvin et al., 2019, Vanaja et al., 2011). Another factor of importance to Norwegian faba bean cultivation is that the area suitable for legume production is expected to increase in northern climates as growing seasons lengthen due to climate warming (Peltonen-Sainio et al., 2013). The continued temperature increase will likely be accompanied by fewer frost days in high latitude areas, and a general growth in daily minimum temperatures (IPCC, 2022). A wider growing season in Norway will allow more varieties to be introduced, and more areas to incorporate faba bean into cropping systems. The extra days in the field allow for more intercepted solar radiation, and the potential utilization of this energy to enhance plant biomass and seed yield (Sellami et al., 2021). This is backed up by the greater seed yield found in this experiment for plants subjected to more degree days during the growing season. Parvin et al. (2019) found that adequate water in reproductive stages is critical to maintain N fixation rates necessary to achieve higher yield and plant biomass. The potential benefits of the changing climate come with a plethora of uncertainties such as erratic precipitation patterns, shifting disease pressure, and declining soil quality. A reliance on extra irrigation, inorganic pest and disease control measures, or inorganic fertilizer treatments can negate the benefits discussed above. All these factors are important when analyzing the degree to which faba bean can influence Norwegian agriculture.

Conclusion

DSW yield data across varieties gave very little conclusive data. Across the two sowing times, though, the extra degree days were possibly a factor in greater yield and lower seed moisture content for the 27 April sowing time plants. N content of 2.4% and a corresponding C:N ratio of 16.9 support previous claims about leaf N as a factor in plant available N. The lower N content in stems and pods reinforces findings that only a small portion of faba bean residue is available for subsequently grown crops. An inverse relationship between HI, and N residue was shown clearly in this data. The balance between plant protein benefits derived from high seed yield (and high HI), and agronomic benefits resulting from high N residue will be important in the utilization of faba bean in Norway as the climate changes, and as agriculture adapts to meet the goals of governments and desires of consumers.

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Abbreviations

BNF: Biological nitrogen fixation

LCA: Life cycle assessment (or analysis)

GHG: Greenhouse gas

GWP: Global warming potential

DSW: Dry seed weight

HI: Harvest index

ha: Hectare

daa: Decare

N: Nitrogen

C: Carbon

N_2: Dinitrogen

N_2O: Nitrous oxide

NH_3: Ammonia

Appendix

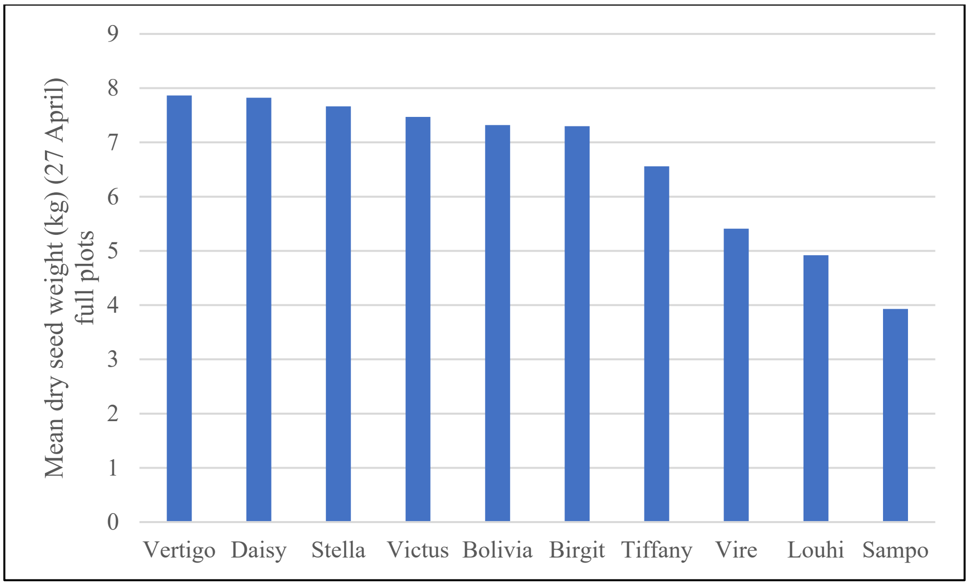


Figure A1. Mean dry seed weight (DSW) (kg) from 27 April sowing time by variety.

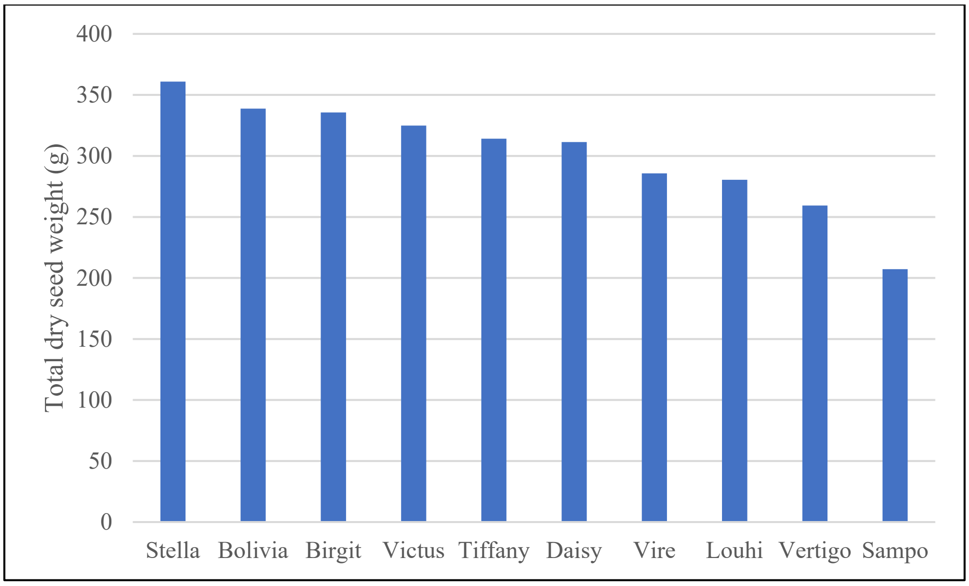


Figure A2. Total dry seed weight (DSW) by variety for the subplots from 14 May sowing time.

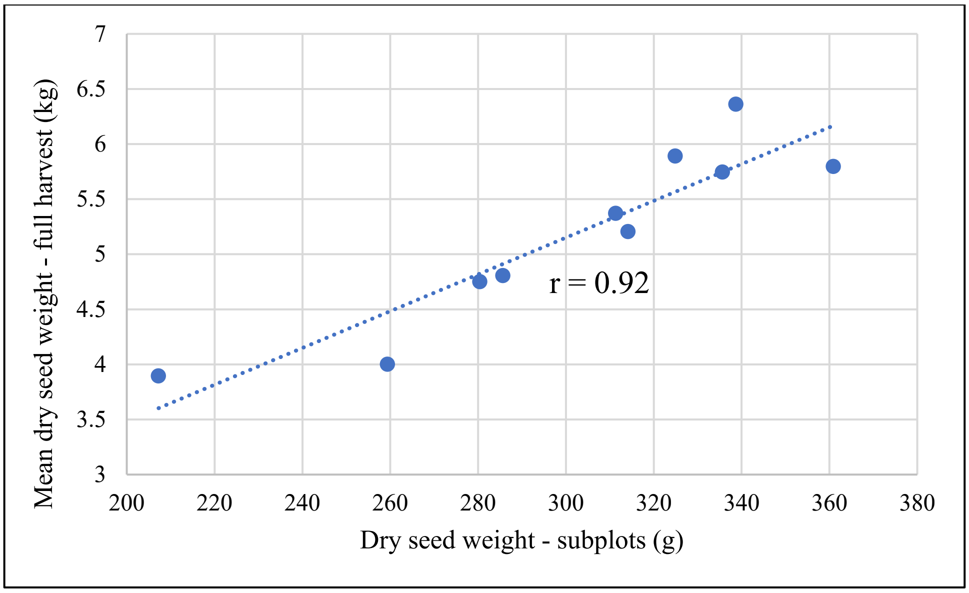


Figure A3. Correlation between subplot dry seed weight (DSW) (g) and full plot mean dry seed weight (DSW) (kg) for the 14 May sowing time.

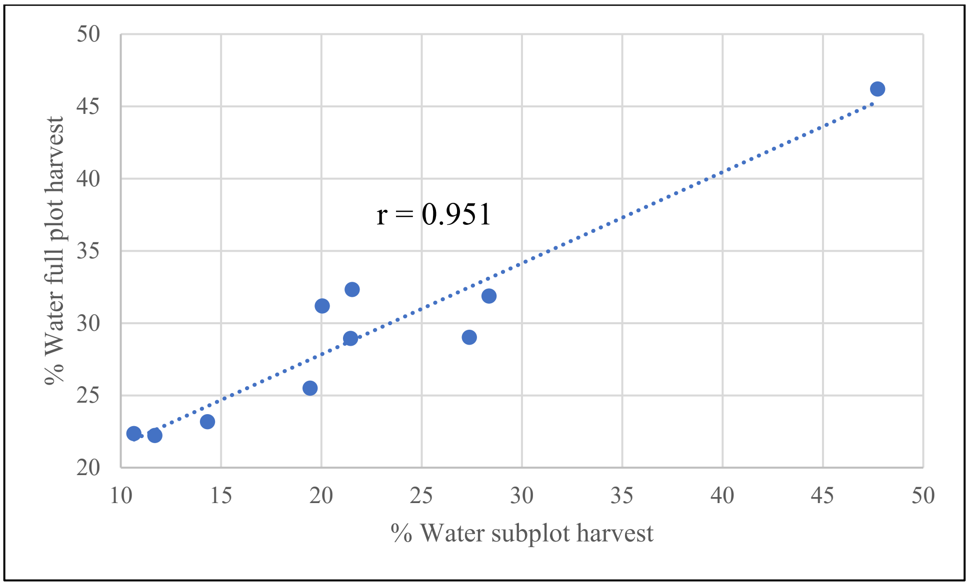
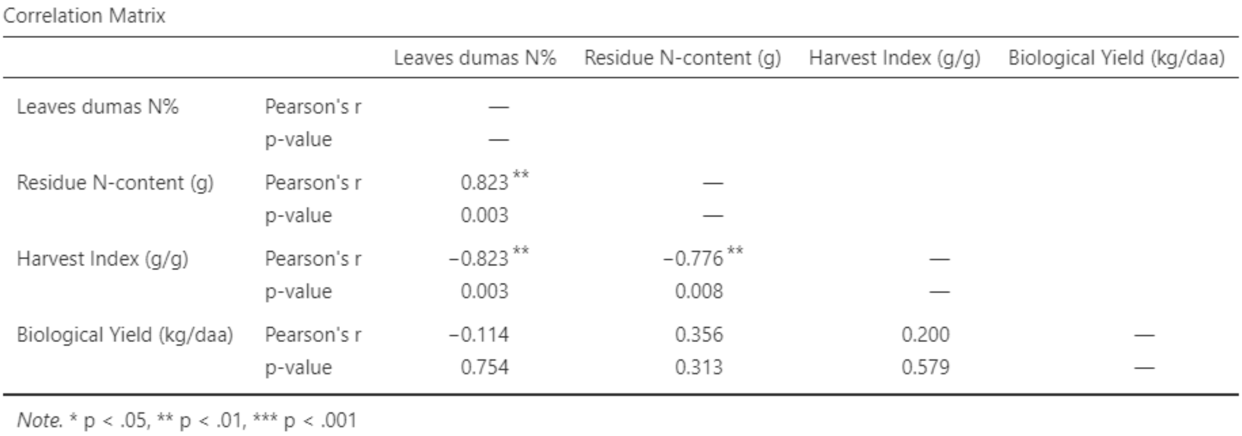


Figure A4. Correlation between moisture content (%) in seeds from the full plot harvest and the subplot harvest from the 14 May sowing time.

Table A1. Correlation matrix between leaves dumas N%, residue N-content (g), harvest index (g g^{-1}), and biological yield (kg daa^{-1}) with Pearson's r and p-value.

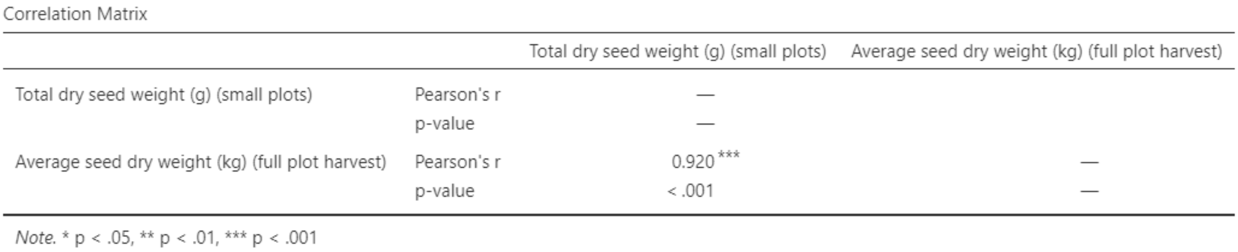


Correlation Matrix

		Leaves dumas N%	Residue N-content (g)	Harvest Index (g/g)	Biological Yield (kg/daa)
Leaves dumas N%	Pearson's r	—			
	p-value	—			
Residue N-content (g)	Pearson's r	0.823 **	—		
	p-value	0.003	—		
Harvest Index (g/g)	Pearson's r	−0.823 **	−0.776 **	—	
	p-value	0.003	0.008	—	
Biological Yield (kg/daa)	Pearson's r	−0.114	0.356	0.200	—
	p-value	0.754	0.313	0.579	—

Note. * p < .05, ** p < .01, *** p < .001

Table A2. Correlation matrix between total dry seed weight (DSW) from subplots and mean yield from full plot harvest with Pearson's r and p-value.

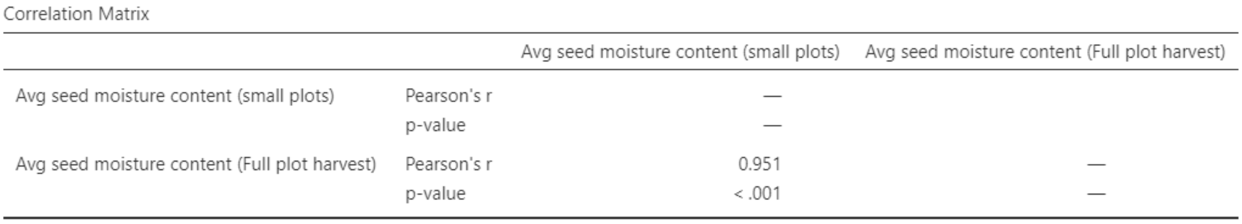


Correlation Matrix

		Total dry seed weight (g) (small plots)	Average seed dry weight (kg) (full plot harvest)
Total dry seed weight (g) (small plots)	Pearson's r	—	
	p-value	—	
Average seed dry weight (kg) (full plot harvest)	Pearson's r	0.920 ***	—
	p-value	< .001	—

Note. * p < .05, ** p < .01, *** p < .001

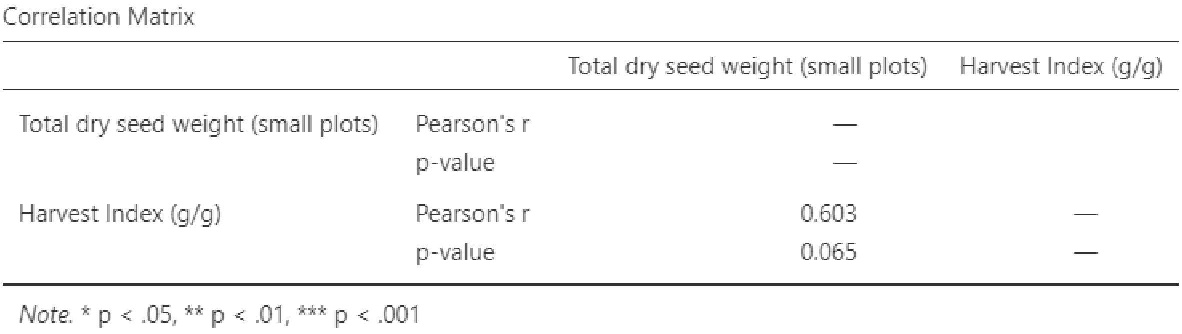
Table A3. Correlation matrix between mean moisture content in subplots and mean moisture content in full harvested plots with Pearson's r and p-value.



Correlation Matrix

		Avg seed moisture content (small plots)	Avg seed moisture content (Full plot harvest)
Avg seed moisture content (small plots)	Pearson's r	—	
	p-value	—	
Avg seed moisture content (Full plot harvest)	Pearson's r	0.951	—
	p-value	< .001	—

Table A4. Correlation matrix for total dry seed weight (DSW) (subplots) (g), and harvest index (g g^{-1}) with Pearson's r and p-value.

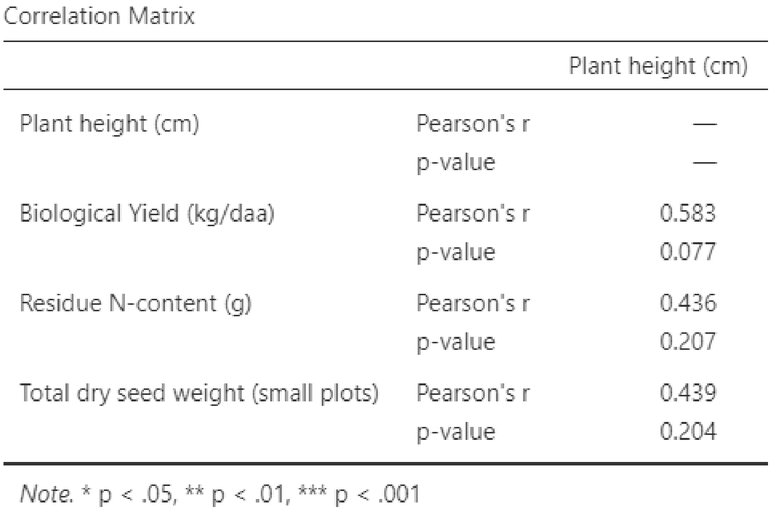


Correlation Matrix

		Total dry seed weight (small plots)	Harvest Index (g/g)
Total dry seed weight (small plots)	Pearson's r	—	
	p-value	—	
Harvest Index (g/g)	Pearson's r	0.603	—
	p-value	0.065	—

Note. * p < .05, ** p < .01, *** p < .001

Table A5. Correlation matrix for plant height, with variables biological yield (kg daa^{-1}), residue N content (g), and total dry seed weight (DSW) (subplots) (g) with Pearson's r and p-value.

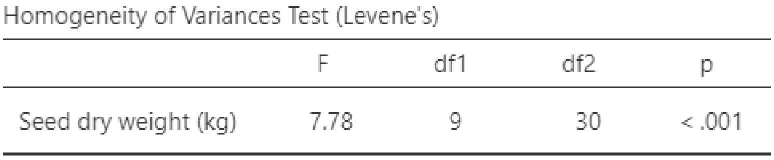


Correlation Matrix

		Plant height (cm)
Plant height (cm)	Pearson's r	—
	p-value	—
Biological Yield (kg/daa)	Pearson's r	0.583
	p-value	0.077
Residue N-content (g)	Pearson's r	0.436
	p-value	0.207
Total dry seed weight (small plots)	Pearson's r	0.439
	p-value	0.204

Note. * p < .05, ** p < .01, *** p < .001

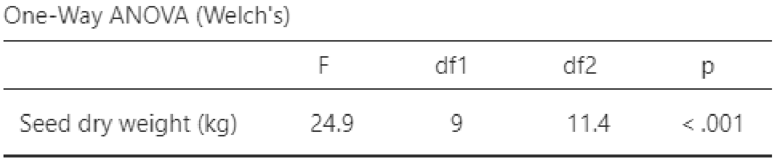
Table A6. Levene's homogeneity of variances test for dry seed weight (DSW) (kg) from both sowing times separated by variety.



Homogeneity of Variances Test (Levene's)

	F	df1	df2	p
Seed dry weight (kg)	7.78	9	30	< .001

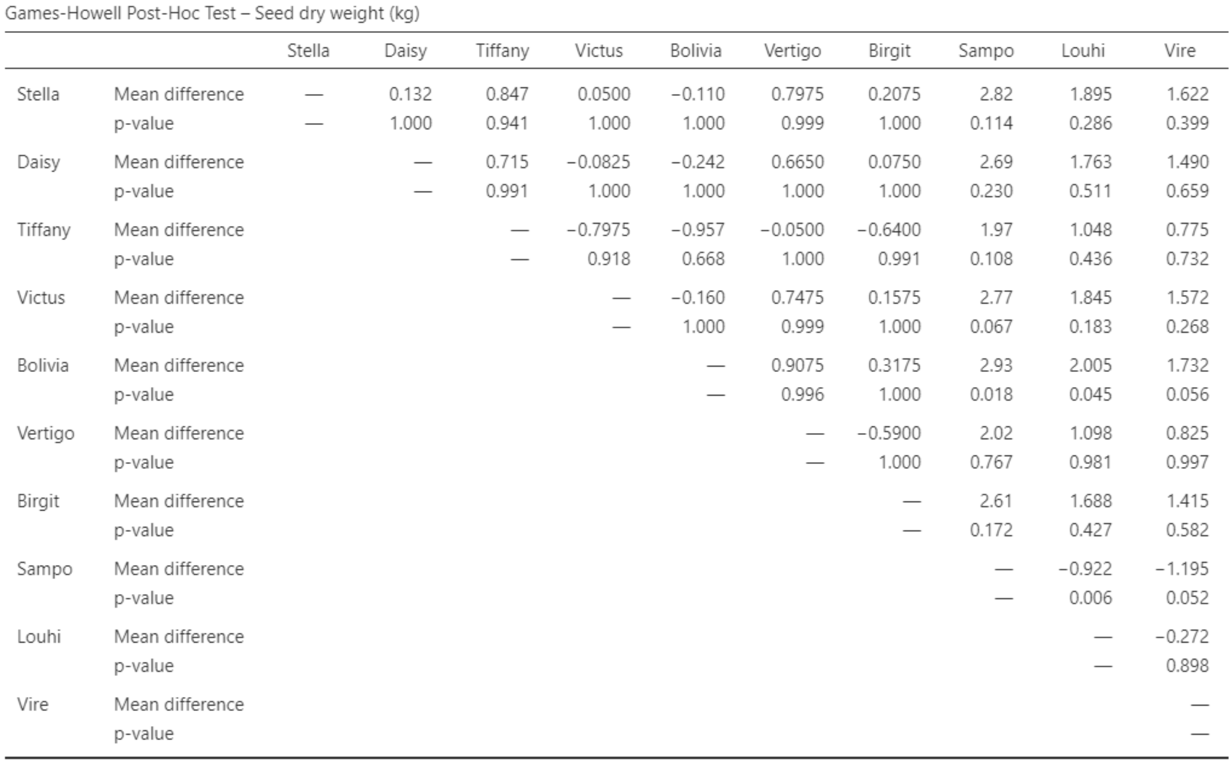
Table A7. Welch's one-way ANOVA test for dry seed weight (DSW) (kg) from both sowing times separated by variety.



One-Way ANOVA (Welch's)

	F	df1	df2	p
Seed dry weight (kg)	24.9	9	11.4	< .001

Table A8. Games-Howell post hoc test for dry seed weight (DSW) (kg) from both sowing times separated by variety.



Games-Howell Post-Hoc Test – Seed dry weight (kg)

		Stella	Daisy	Tiffany	Victus	Bolivia	Vertigo	Birgit	Sampo	Louhi	Vire
Stella	Mean difference	—	0.132	0.847	0.0500	−0.110	0.7975	0.2075	2.82	1.895	1.622
	p-value	—	1.000	0.941	1.000	1.000	0.999	1.000	0.114	0.286	0.399
Daisy	Mean difference		—	0.715	−0.0825	−0.242	0.6650	0.0750	2.69	1.763	1.490
	p-value		—	0.991	1.000	1.000	1.000	1.000	0.230	0.511	0.659
Tiffany	Mean difference			—	−0.7975	−0.957	−0.0500	−0.6400	1.97	1.048	0.775
	p-value			—	0.918	0.668	1.000	0.991	0.108	0.436	0.732
Victus	Mean difference				—	−0.160	0.7475	0.1575	2.77	1.845	1.572
	p-value				—	1.000	0.999	1.000	0.067	0.183	0.268
Bolivia	Mean difference					—	0.9075	0.3175	2.93	2.005	1.732
	p-value					—	0.996	1.000	0.018	0.045	0.056
Vertigo	Mean difference						—	−0.5900	2.02	1.098	0.825
	p-value						—	1.000	0.767	0.981	0.997
Birgit	Mean difference							—	2.61	1.688	1.415
	p-value							—	0.172	0.427	0.582
Sampo	Mean difference								—	−0.922	−1.195
	p-value								—	0.006	0.052
Louhi	Mean difference									—	−0.272
	p-value									—	0.898
Vire	Mean difference										—
	p-value										—

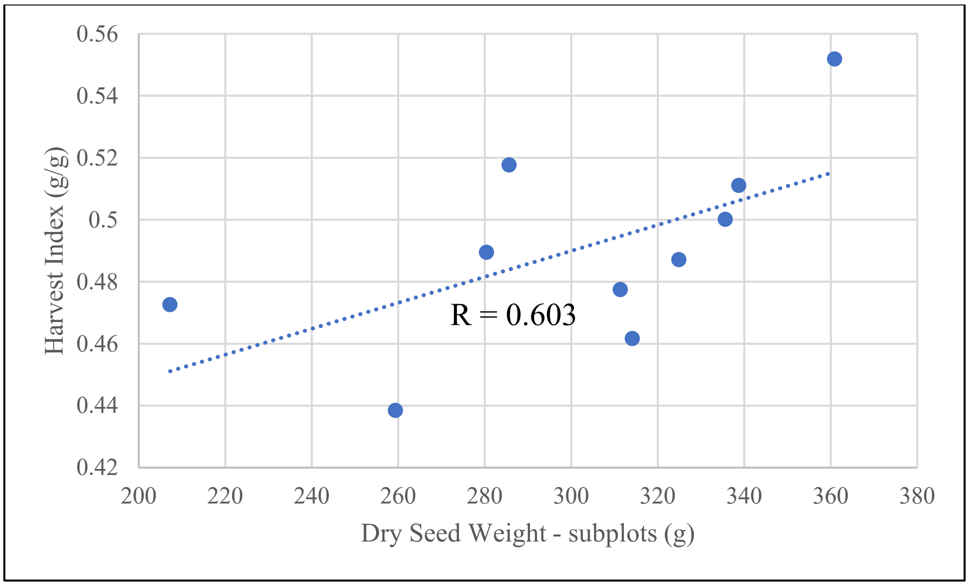
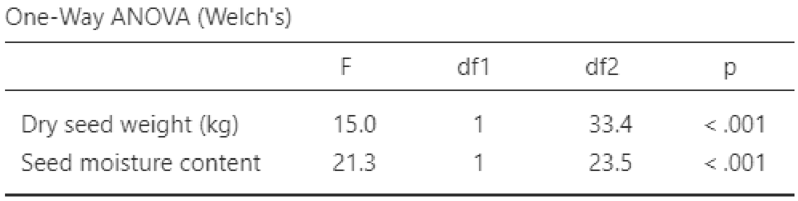


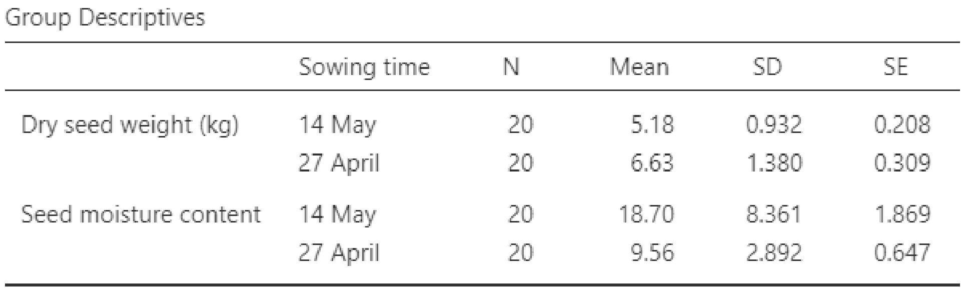
Figure A5. Correlation between harvest index (g g-1) and dry seed weight (DSW) (subplots) (g) with Pearson's r value.

Table A9. Welch's one-way ANOVA and group descriptives for dry seed weight (DSW) (kg) and seed moisture content across the two sowing times (27 April, 14 May).



One-Way ANOVA (Welch's)

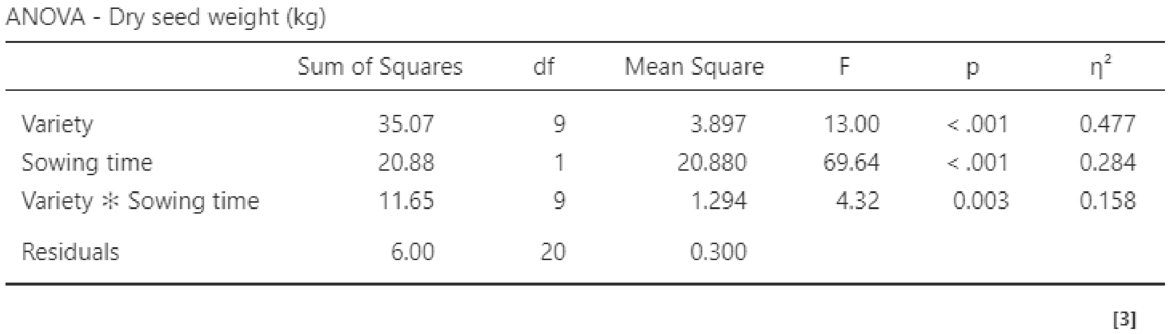
	F	df1	df2	p
Dry seed weight (kg)	15.0	1	33.4	< .001
Seed moisture content	21.3	1	23.5	< .001



Group Descriptives

	Sowing time	N	Mean	SD	SE
Dry seed weight (kg)	14 May	20	5.18	0.932	0.208
	27 April	20	6.63	1.380	0.309
Seed moisture content	14 May	20	18.70	8.361	1.869
	27 April	20	9.56	2.892	0.647

Table A 10. ANOVA test for variety and sowing time effect on dry seed weight (DSW) (kg) for all four varietal repititions across both sowing times. Levene's homogeneity of variances test, and Shapiro-Wilk normality test assumption checks are included.

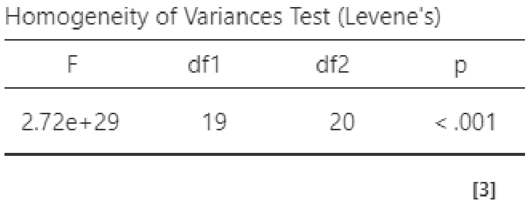


ANOVA - Dry seed weight (kg)

	Sum of Squares	df	Mean Square	F	p	η^2
Variety	35.07	9	3.897	13.00	< .001	0.477
Sowing time	20.88	1	20.880	69.64	< .001	0.284
Variety ✻ Sowing time	11.65	9	1.294	4.32	0.003	0.158
Residuals	6.00	20	0.300			

[3]

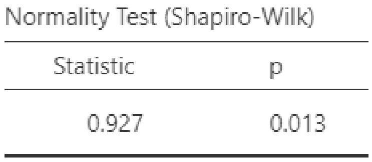
Assumption Checks



Homogeneity of Variances Test (Levene's)

F	df1	df2	p
2.72e+29	19	20	< .001

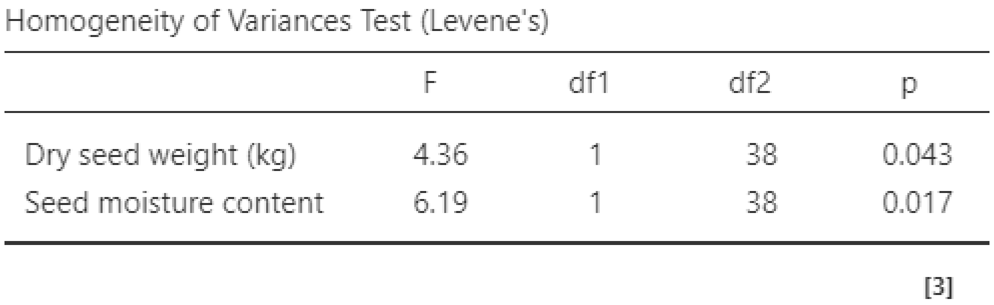
[3]



Normality Test (Shapiro-Wilk)

Statistic	p
0.927	0.013

Table A11. Levene's homogeneity of variances test for dry seed weight (DSW) and seed moisture content across the two sowing times (27 April, 14 May).

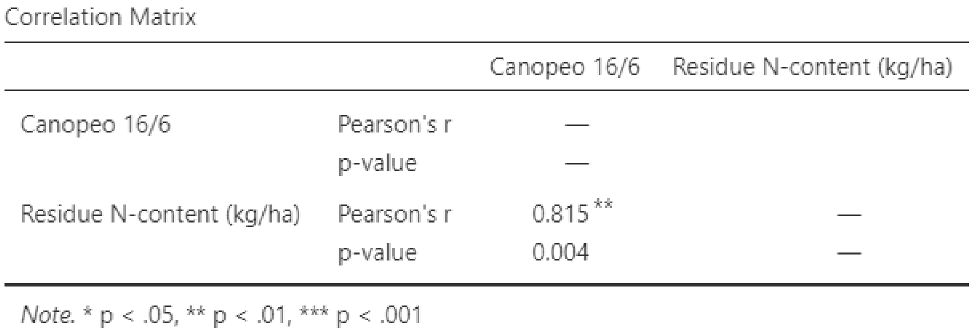


Homogeneity of Variances Test (Levene's)

	F	df1	df2	p
Dry seed weight (kg)	4.36	1	38	0.043
Seed moisture content	6.19	1	38	0.017

[3]

Table A 12. Correlation matrix for mean Canopeo canopy cover (%) and residue N content (kg ha^{-1}) with Pearson’s r and p-value.

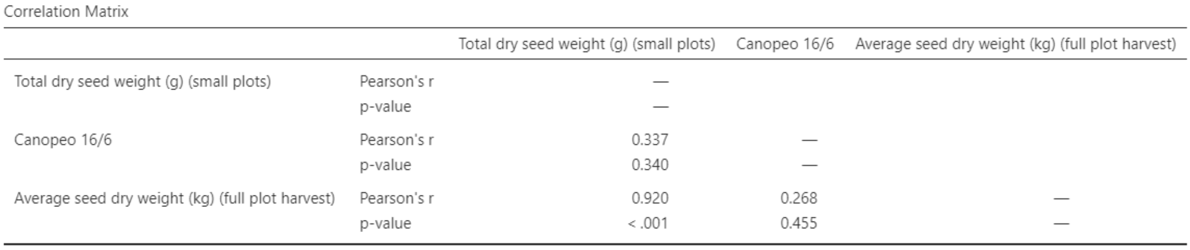


Correlation Matrix

		Canopeo 16/6	Residue N-content (kg/ha)
Canopeo 16/6	Pearson's r	—	
	p-value	—	
Residue N-content (kg/ha)	Pearson's r	0.815 **	—
	p-value	0.004	—

Note. * p < .05, ** p < .01, *** p < .001

Table A13. Correlation matrix for mean Canopeo canopy cover (%), total dry seed weight (g) subplots, and average seed dry weight (kg) full plot harvest with Pearson’s r and p-value.



Correlation Matrix

		Total dry seed weight (g) (small plots)	Canopeo 16/6	Average seed dry weight (kg) (full plot harvest)
Total dry seed weight (g) (small plots)	Pearson's r	—		
	p-value	—		
Canopeo 16/6	Pearson's r	0.337	—	
	p-value	0.340	—	
Average seed dry weight (kg) (full plot harvest)	Pearson's r	0.920	0.268	—
	p-value	< .001	0.455	—

Table A14. Subplot harvest measurements

Variety / plot	# plants	avg plant length	# pods	Pods /plant	# seeds	Seeds /pod	Seeds /plant	total fresh seed weight (g)	dry seed weight (g)	dry leaf weight (g)	dry pod weight (g)	dry stem weight (g)	total dry weight (g)	total dry weight (g/ plant)	total seed moisture content (g)	% moisture
Stella 2102	34	105.65	171	5.03	581	3.40	17.09	448.05	360.91	54.69	77.03	161.44	654.07	19.24	87.14	19.45
Vire 2106	44	97.82	234	5.32	734	3.14	16.68	319.74	285.65	37.64	90.53	138.02	551.84	12.54	34.09	10.66
Tiffany 2107	54	105.5	184	3.41	512	2.78	9.48	438.55	314.16	55.14	88.78	222.47	680.55	12.60	124.39	28.36
Birgit 2108	39	102.59	183	4.69	588	3.21	15.08	427.8	335.65	46.28	94.216	195.02	671.166	17.21	92.15	21.54
Louhi 2202	44	100.5	232	5.27	714	3.08	16.23	317.59	280.42	54.05	88.6	149.88	572.95	13.02	37.17	11.70
Sampo 2206	35	97.54	239	6.83	731	3.06	20.89	241.92	207.25	45.53	82.09	103.68	438.55	12.53	34.67	14.33
Vertigo 2207	40	113.11	158	3.95	444	2.81	11.10	496.31	259.39	49.06	92.67	190.52	591.64	14.79	236.92	47.74
Bolivia 2404	33	124.79	175	5.30	623	3.56	18.88	423.71	338.74	42.89	85.13	196.1	662.86	20.09	84.97	20.05
Victus 2502	39	121.41	162	4.15	493	3.04	12.64	413.73	324.93	72.36	70.69	199.13	667.11	17.11	88.8	21.46
Daisy 2602	39	117.72	144	3.69	463	3.22	11.87	428.77	311.37	57.16	74.27	209.37	652.17	16.72	117.4	27.38

Table A15. Kjeldahl N, Dumas N, C, and Sulfur (S) content from laboratory analysis.

Variety / plot	Seed Kjeldahl-N%	Rough Stem Kjeldahl-N%	Fine Stem Dumas N%	Fine Stem Dumas C%	Fine Stem S%	leaves dumas N%	Leaves Dumas C%	Leaves Dumas S%	Pods Dumas N%	Pods Dumas C%	Pods Dumas S%
Stella 2102	4.4	0.5	0.8	40.4	0.05	2.2	40.1	0.09	1.3	40.5	0.03
Vire 2106	4.6	0.8	1	39.4	0.03	2.2	40	0.05	1.2	40.9	0.01
Tiffany 2107	4.5	0.6	0.7	39.9	0	2.5	40.5	0.06	1.3	41.3	0
Birgit 2108	4.4	0.5	0.8	40.4	0.06	2.2	40.4	0.04	1.3	41.2	0
Louhi 2202	5.1	0.6	0.9	39.9	0.03	2.4	40.9	0.07	1.1	41.5	0
Sampo 2206	5.2	0.7	1	38.9	0.03	2.5	40.5	0.07	1.7	40.9	0.02
Vertigo 2207	4.3	0.6	0.7	40.2	0	2.6	40.6	0.06	1.6	41.1	0.01
Bolivia 2404	4.3	0.5	0.7	40.1	0.02	2.3	41.2	0.06	1.4	41.7	0.01
Victus 2502	4.5	0.4	0.6	40.2	0	2.6	40.7	0.01	1.5	41.6	0.06
Daisy 2602	4.6	0.5	0.8	40	0.02	2.5	40.7	0.05	1.3	40.5	0

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