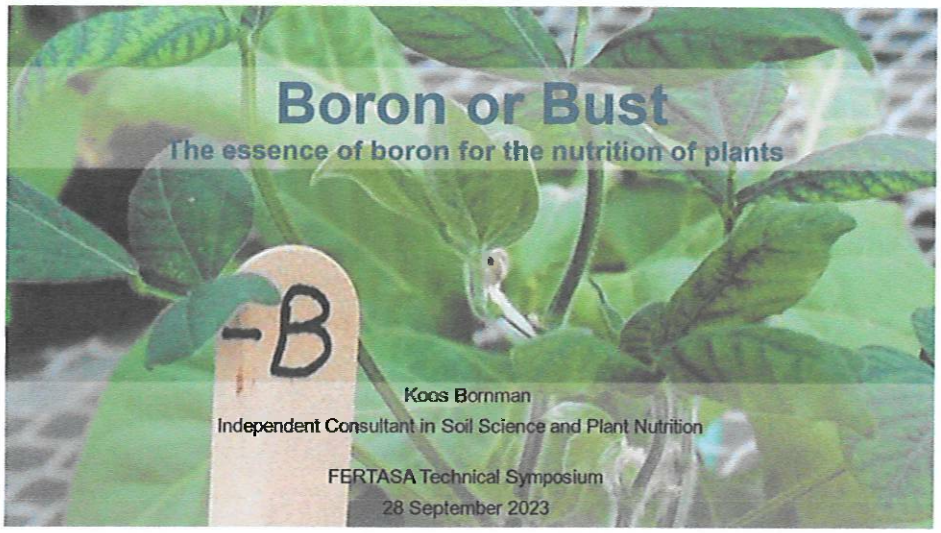

Boron or Bust

The essence of boron for the nutrition of plants

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FERTASA Technical Symposium
28 September 2023

Content

- Boron as element
- Boron in human physiology
- Boron in the soil biome
- Boron as essential plant nutrient
- Boron functions in the plant
- Plant requirement of boron
- Factors affecting uptake of boron from the soil
- Boron fertilizers
- Boron interaction with other elements
- Boron mobility within the plant
- Crop response to boron nutrition if deficient (examples of 11 crops)
- Conclusion



What this presentation does not expand on

- Soil and tissue norms of boron
- Methods of analyses of boron (plant tissue and soil)
- Recommended applications of boron
- Comparison of boron products
- Boron toxicity in higher plants

Barker and Pilbeam, 2007
Abat, 2015
McLaughlin, 2015
De Gryse, 2016

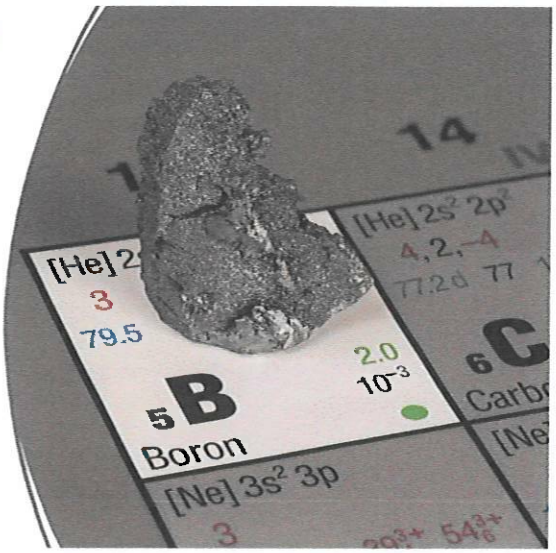


Boron toxicity in soybean

General facts on boron as element

- Name originated from the Arabic word "buraq", the name for borax
- Lightest element in group 13 (boron group) of the periodic table
- An element with atomic number 5 with symbol B, atomic mass of 10,811, oxidation state 3, prone to forming covalent bonds. **Metallic and non-metallic properties.**
- **Only found in ionic form** (salt form) in the earth's crust
- Originally used as flux for goldsmithing or glaze for pottery, before formally discovered (isolated) in 1808 by two French and one British scientist
- **Regarded as a rare earth material**
- Source material is especially borax, kernite and tincalconite. It is also found in in the minerals colemanite, ulexite and tourmaline
- Primarily mined in Turkey and California
- It is used as a **semiconductor**, hardener of steel and oxidizer. It is also used in the manufacturing of glass, detergents and even the **medical field** from an agent in eyedrops to being used as **isotope for radiating cancerous tumors** (especially brain tumors)

https://www.britannica.com/science/boron#chemical-element
https://en.wikipedia.org/wiki/Boron



Brains, bones and boron
Boron and human (animal) health



Mardinoglu et al., 2020

Boron plays a pertinent role in the following aspects of human metabolism;

- Reproduction
- Development of the body
- Calcium metabolism
- **Bone formation** and bone health (absorption of calcium) – prevention of osteoarthritis
- **Brain and central nervous system function**
- Insulin metabolism
- Energy substrate metabolism
- **Facilitation of the metabolism and function of steroid hormones like vitamin D, estrogen, testosterone, progesterone**
- Metabolism within the thyroid
- Metabolism of vitamins and minerals
- **Immunity and prevention of certain cancers**

Nielsen, 2016, Wilson, in Healthline 2019, US NIH, 2022

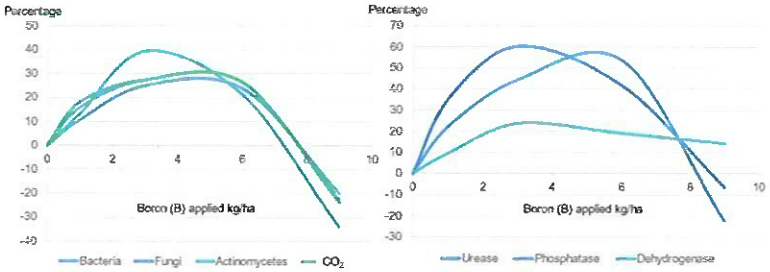
Boron nutrition of humans

- **No adverse effects of high boron have been recorded from food and water sources.**
- The recorded median consumption of adult humans varies between 0,5 to 1,5 mg/day
- Less than 1 mg B per day inhibits the health benefits of boron.
- Up to 13 mg B intake per day is regarded as safe.
- Dietary supplements contain 0.15 to 6 mg B
- The primary foods for boron supplementation are fruit, tubers, legumes and milk products
- The **recorded foods high in boron** that is mostly consumed are apples, coffee, dried beans, milk, cheese, potatoes, fruit juices, wine, cider and beer
- Recorded toxicity of boron in humans is extremely rare and if so, its source was household cleaners or pesticides.
- **More than 15 g B intake is regarded fatal to humans.** That is equivalent to **16 teaspoons of borax. Ten teaspoons of table salt** will kill a human of 75 kg

Boron is an essential element for the soil biome

Recent studies indicate that boron is an essential microelement for the soil biome as for higher plants

Example of a study in Turkey where boron was applied at different rates to a 1,8% carbon clay loam under wheat (data used from Bilen, Bilen & Bardhan, 2011)

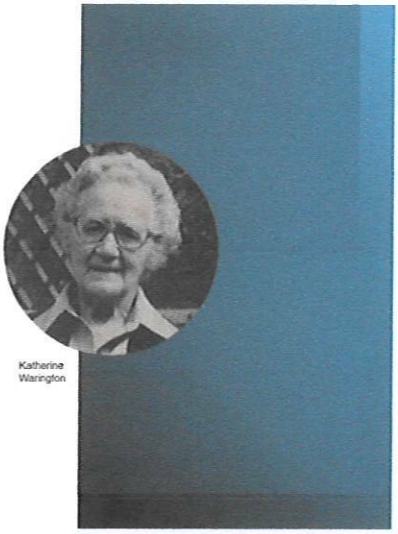


Figures above; Increase/decrease relative to the control of micro-organism count and CO_2 production as well as enzyme activity at different levels of boron (B) applied to the topsoil at flowering of wheat (curve fitments all above R^2 of 0,80)

Other references
Sun et al., 2012
Hemkemeyer et al., 2021

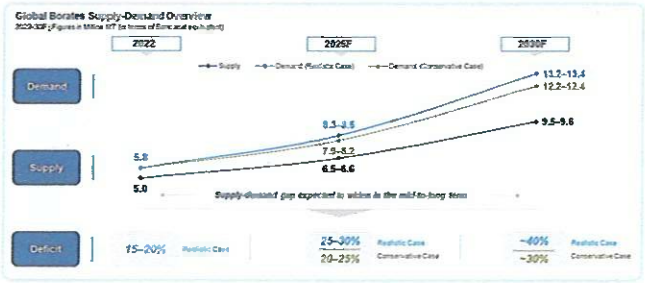
A century ago, boron was identified as an essential plant nutritional element (some introductory facts)

- Boron (B) is one of the eight essential micronutrients for plants
- It is the **only non-metal** among the plant micronutrients
- In 1923, it was **first** time reported that boron is essential for the **cell structure** of plants (Warington, 1923).
- In 1983 boron was also identified as part of plant **cell membranes** (Parr & Loughman, 1983; Welch, 1995; Ahmad et al., 2009)
- It is the only nutritional element that may be **taken up by plants in non-ionic form** e.g., H_3BO_3 or $B(OH)_3$ (Mengel & Kirkby, 1982; Marschner, 1995) It also exists in plants in the $B(OH)_4^-$ form at high pH, but in very low concentrations.
- **Boron deficiency is one of the major constraints to crop production** (Sillanpaa, 1982), and has been reported in more than 80 countries and for 132 crops over the last 60 years (Shorrocks,1997).
- Boron deficiency has been realized as the **second most important micronutrient constraint in crops** after that of zinc on a global scale (Ahmad et al., 2012)
- **The uptake and transport of boron is complex** (Brown & Hu,1998, Brown et al., 2022)



Katherine Warington

Boron fertilizer demand will double in the next 10 years, but it seems boron supply will soon be inadequate





Published by Precedence Research 21 August 2023

"The decarbonization-led future with applications of e-mobility, wind energy, and solar energy is expected to drive an unprecedented rise in demand for boron and its derivatives."

https://www.aranca.com/knowledge-library/articles/business-research/boron-revolution-2030-quest-for-resilience-amidst-supply-demand-disparity

Some basic boron fertilizers

(See USDA report, 2022 for a comprehensive list)

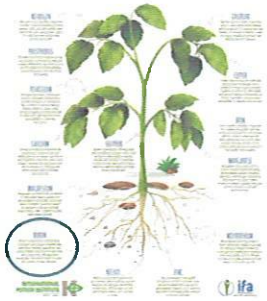
Fertilizer	Formula	Boron content (%)	Solubility (g in 100 g water)
Sodium tetraborate	$Na_2B_4O_5.5H_2O$	14	1,06
Borax (sodium tetraborate decahydrate)	$Na_2B_4O_7.10H_2O$	11	2
Dehybor (anhydrous borax)	$Na_2B_4O_7$	22	NS
Boric acid	H_3BO_3	18	5.2 (20 degrees C)
Sodium polyborate (Solubor)	$Na_2B_{10}O_{13}.4H_2O$	21	As boric acid Tends to supersaturate
Colemanite (pure)	$Ca_2B_6O_{11}.5H_2O$	16	0.3
Colemanite (fertilizer)	$Ca_2B_6O_{11}.5H_2O$ With impurities	9–14	NS
Ulexite (Chilexite)	$NaCaB_5O_9.8H_2O$	13	NS
Fritted boron-silicate	-	10–15	NS



The pKa value of boric acid is 9,15. The pH of a 4% solution is approximately 5

NS = not readily soluble

Handbook of Chemistry and Physics, 62 ed, 1982, Turner & Turner, 2021, USDA report, 2022



Mortvedt et al., 1971
Kohli et al., 2002
Barker and Pilbeam, 2007
Marschner, 2012 (3rd ed)
Cakmac, 2017
Shireen et al., 2018
Jakanovic, 2022

Roles and functions of boron in the plant

- **Root elongation**
- Regulates lignification
- **Cell wall** synthesis and structure integrity
- **Cell membrane** function
- **Carbohydrate metabolism & transport**
- Protein, amino acid and nitrate metabolism **(NUE)**
- Ribose Nucleic Acid (RNA) metabolism
- Influences respiration **(WUE)**
- Regulates indole acetic acid metabolism (IAA of the **auxin** group)
- **Phenol metabolism** (controls phenol concentration)
- **Ensuring pollen viability** flower formation and seed production
- **Supporting disease resistance** – various mechanisms – also reduces polyphenols and toxic products of phenol oxidation (ROS). Indirectly serves as **antioxidant**

ROS = reactive oxygen species

Boron requirement of some field and horticultural crops

High	Medium	Low
Alfalfa	Asparagus	Barley
Apple	Carrot	**Beans**
Brassicas	Cotton	Blueberry
Celery	Cherry	Cereals
Clovers	Lettuce	**Citrus**
Mustard	Onion	Cucumber
Peanuts	Parsnip	Flax Grasses
Rape (Canola)	Peach	**Maize**
Red beet	Pear	Oat
Rutabaga	Potato (sweet)	Peas
Sugar beet	Radish	Pepper
Sunflower	Spinach	**Potato (white)**
Turnip	Sweetcorn	Raspberry
	Tobacco	Rye
	Tomato	Sorghum
		Strawberry
		Wheat

Note: Based on rates of fertilizer application of boron recommended by state agricultural agencies in the United States

a high requirement is a recommended fertilization exceeding 2 kg B ha $^{-1}$;

a medium requirement is fertilization with 1 to 2 kg B ha^{-1}; and

a low requirement is fertilization with less than than to 1 kg B ha $^{-1}$.

Adapted from Mortvedt J.J. and Woodruff J.R., in *Boron and Its Role in Crop Production*. CRC Press, Boca Raton, FL, 1993, pp. 157 –176.

Factors affecting boron uptake by plants

- Soil type (**texture** and **clay mineralogy**)
- Light conditions and **rate of growth (ROS build up)**
- Alkalinity, calcareousness and salinity (Panday et al., 2019)
- **Cultivation method** (no till lessens boron availability) Lal et al., 1998
- **Soil pH (low and high)**
- Organic matter content
- Boron concentration in soil solution
- Soil moisture
- **Plant species and genotype**
- Boron content of **irrigation water**
- Boron **interaction** with other plant nutrients and elements (N, P, K, Ca, Mg, Zn and Al

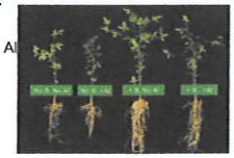


Cakmak and Romheld, 1997 (Canola)



Hydrated oxides of Al and Fe, adsorbing $H_2BO_3^-$

Bornman et al., 1998

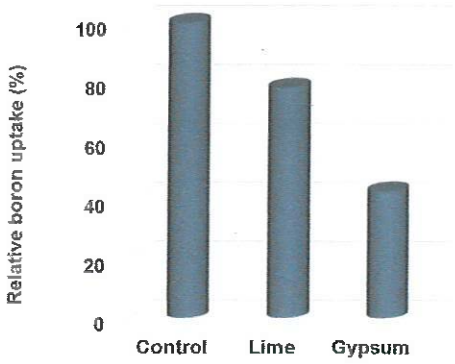


Riaz et al., 2018
Trifoliate orange

Ahmad et al., 2012
Pandey et al., 2019

Lenoble et al., (1996) concluded that boron additions may need to be increased under acid, high aluminium soils, because applications of boron prevented aluminium inhibition of root growth on acid, aluminium -toxic soils.

Impact of high lime and especially gypsum application on the boron uptake of maize on a sandy soil

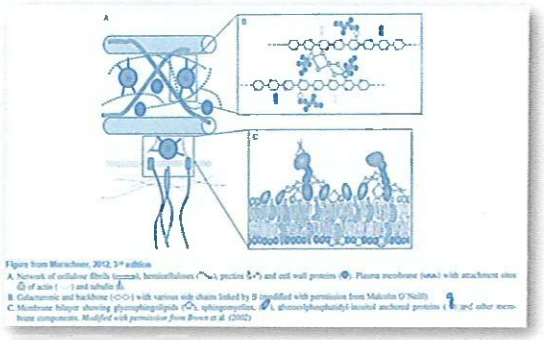


Bomman 1993, Over liming studies on maize and wheat in glasshouse trials.
Bomman, Bomman & Barnard, 1998
Matula, 2004

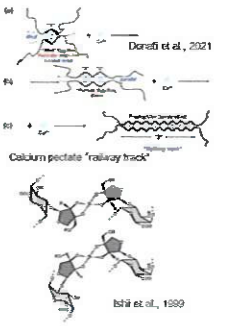
Boron affects the efficiency of other nutritional elements

Some examples

Calcium and boron strengthens cell walls and membranes

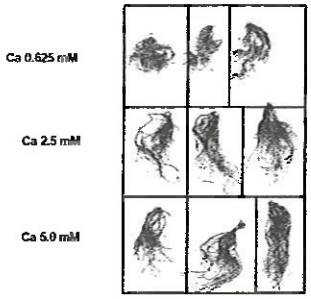


Hu & Brown, 1994, Brown et al., 2002



Boron diester = Rhamnogalacturonan II (RG-II)

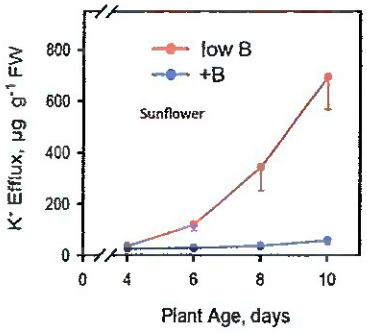
Boron and calcium interaction supports root growth



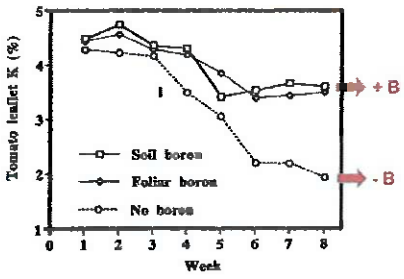
Roots of rose (Rosa rubiginosa)

Gammore-Neumann and Davidov, 1993. Plant and Soil 155/56:155-154

Boron strengthens cell walls and membranes to prevent potassium leakage and enhances its uptake

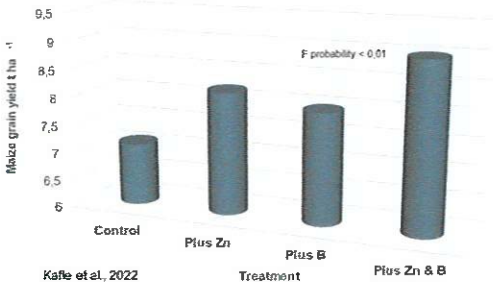


Cakmak et al., 1995



Davis et al., 2003

Boron enhances the efficiency of zinc as nutrient (e.g., maize)



Kafle et al., 2022

Phosphorous uptake by plants is also enhanced if treated with boron (Pollard et al., 1977)

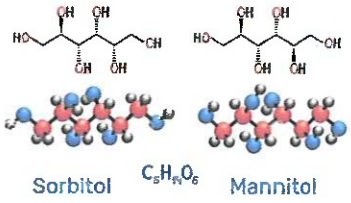
Faba beans and maize uptake of phosphorous increased 215% and 176% respectively when treated with boron

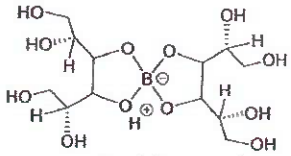
Also refer to work done on rapeseed by Zhao et al., 2020

Similar results: Melgar, 2001, Wasaya et al., 2017

Boron uptake and mobility within the plant

- The supplying mechanism of boron to plant roots is primarily through **mass flow**, while its distribution in plants is governed by the **transpiration stream through the xylem** (Raven, 1980).
- Evidence exists that **boron uptake is passive and metabolic active** (Brown et al., 2002)
- Boron is relatively (phloem) immobile in the plant, and thus its **availability is essential at all stages of growth**, especially during fruit and seed development. (Aftab et al., 2022)
- Physiological studies have revealed the presence of channel -mediated facilitated diffusion and energy -dependent **active transport against concentration gradients** in boron transport systems (Dannel et al., 2000, 2001; Brown et al., 2002, Stangoulis et al., 2001, Pereira et al., 2021)
- **Boron mobility** seems higher in plants rich in **sorbitol/mannitol/fructose** (Hu et al., 1997)





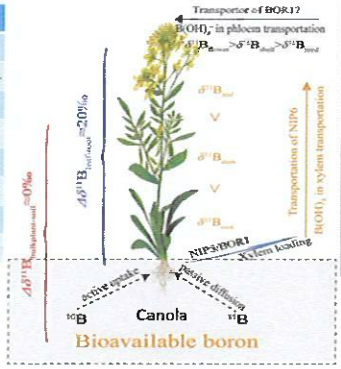
Mannitol boron complex
Lavanya et al., 2020

Some crops in which boron is phloem immobile
Boron mobility may also differ between genotypes

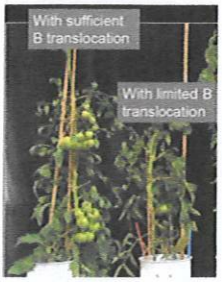
Agronomic	Vegetable	Tree
Alfalfa	Green bean	Fig
Canola (limited)	Lettuce	Pecan
Cotton	Potato	Pistachio
Groundnuts	Tomato	Walnut
Maize		
Sorghum		
Tobacco		
Wheat		

https://agriculture.borax.com/resources/agronomic-notes/boron-in-plant-nutrition/boron-mobility-in-various-plant-species

Note, contrary to calcium, boron foliar sprays are quite effective, e.g., potatoes – Tariq et al., 2022



Xiao et al., 2022



Brown and Shelp, 1997
Brown & Hu 1998
Brown et al., 1999
Brown et al., 2002
Noguchi et al.., 2000;
Ma et al.., 2004
Aftab et al., 2022
Bolanos et al., 2023

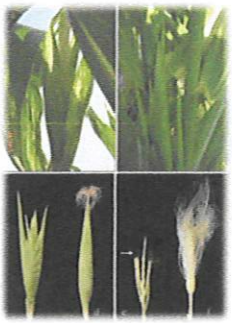
Examples of crop response to boron treatment (when it is deficient)

Quantification of yield and quality response

Maize



General symptoms



Symptoms of B deficiency of maize (cv. NS72) grown in sand culture without added B at anthesis, showing white stripes or transparent streaks on leaf lamina (a), multiple ears (b, c) and short silks (e: arrow, removed husk) compared with normal ear (d, f: ear after removal of husk)







Shrivelled anthers (b) and narrow thin anthers (c), compared with normal anthers (d)

https://www.researchgate.net/figure/Male-inflorescences-of-maize-cv-NS72-plants-grown-without-B0-added-B-small-tassel_fig2_226577962

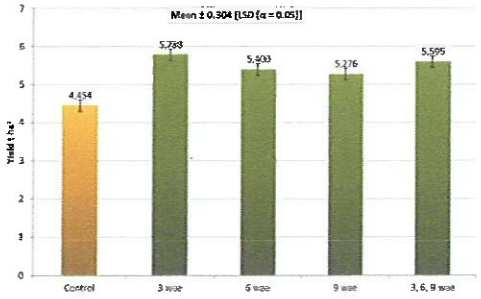


Maize trials with boron in South Africa

Twelve trials of Omnia Nutriology® Solution Development across the maize producing areas over three consecutive seasons have shown boron treatment responses in maize seed yield increase from 3% to 30% (median 5%) with trial mean yields of between4 and 11 t ha^{-1}



Example of maize response to boron on a sandy soil in the Northwest Province



Omnia Nutriology® project CAW-2008-14

Maize response to boron treatment from international trials

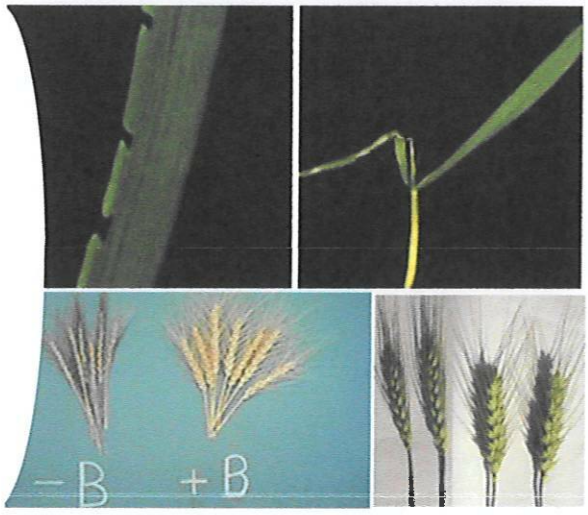
Attribute	Result
Seed yield increase above control	6% to 35% increase Median 12%, n = 28)
Total biomass	58% increase
Protein	**18% increase**
100 grain weight	22% increase
Oil content	10% increase

Ventimiglia et al., 1999
Melgar, et al. 2001
Lordkaew et al., 2010
Tahir, 2012
Adotey, 2020
US Borax, 2023
Brandt, 2023

Wheat

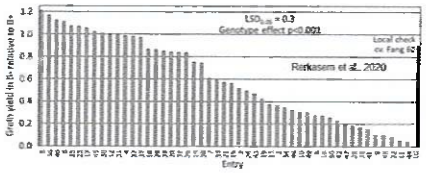


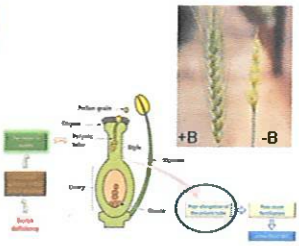
General symptoms



Wheat response to boron treatment

Attribute	Result
Yield increase above control	2% to five fold increase Median 18%, n = 55
1000 seed mass	11 to 13% increase
Harvest index	2% to 3% increase
Pollen germination	7% to 63% increase
Grain per spike	50% to 89%
Grain set	10-fold increase





Mann and Rerkasem, 1992
Rerkasem and Jamjod, 2004
Tahir et al., 2009
Scanlan and Brennan, 2015
Lazgari et al., 2016
Rerkasem et al., 2020

Canola

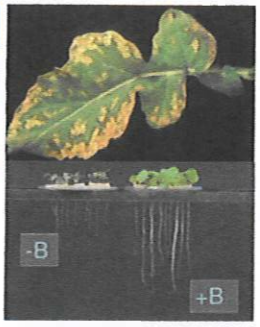


General symptoms



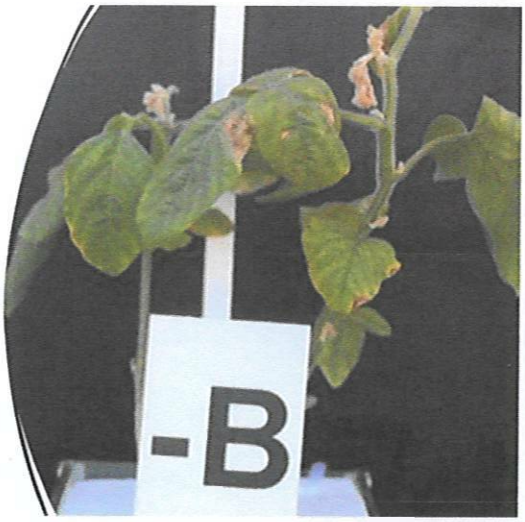
Canola response to boron treatment

Attribute	Result
Yield increase above control	1% to 77% increase Median 8%, n = 25
Oil content	0,5% to 5% increase
Protein content	0,4% to 9% increase



Malhi et al. 2002
Wiens, 2020
AFP Ag, 2023
Brennan, 2023
Mosaic, 2023

Soybean

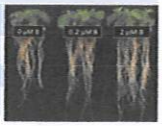


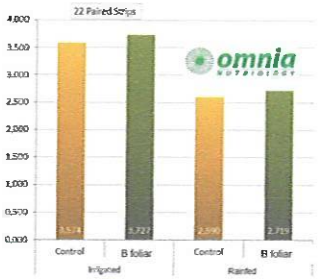
General symptoms



Soybean response to boron treatment

Attribute	Result
Seed yield increase above control (South Africa)	4% to 5% increase Two Omnia Nutriology® trials in KZN Trial code Soybean-HB Foliar-KZN-2005
International trials	
Seed yield increase internationally	3% to 45% increase Median=13%, n=19
Photosynthetic rate	33% increase
Water use efficiency	46% increase
Carboxylation efficiency	50% increase





Yield response of treated strips statistically significant (p=0.01)
16 of the 22 strips showed a yield increase

Woodruff, 2007
Slaton, 2013
Adotey and Yin, 2020
Galeriani et al., 2022
US Borax, 2023

Sunflower



General symptoms



Sunflower response to boron treatment

Attribute	Result
Yield increase above control **(South African data** in KZN, 1976) Empty seeds 100 seed mass	38% increase 28% decrease 18% increase
International data	
Yield increase above control	9% to 25% increase Median = 18%, n = 20
Protein	5% to 19% increase
Oil	13% increase
NUE (Agronomic / Physiological)	**45% / 14% increase**
WUE	**9% to 25% increase**



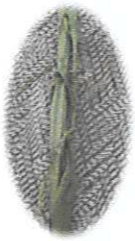
Blamey, 1976
Shehzad et al., 2016
Mehmood et al., 2017
Indu and Singh, 2020
Mahapatra et al., 2021

Sugarcane



Sugarcane response to boron treatment

Attribute	Result
Yield increase above control	4% to 77% increase Median = 18%, n = 10
Sucrose production	**2% to 20% increase**
Brix	3% to 19% increase
Sucrose purity	**7% to 47% increase**
Protein	37% increase

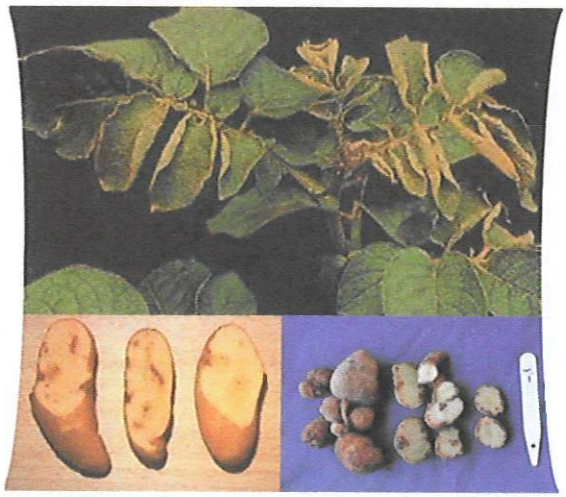


Zapata, 1972
Singh et al., 2015
Mosaic AgriFacts, 2017
Mangrio et al., 2020
Titshall, 2022

Potato



General symptoms

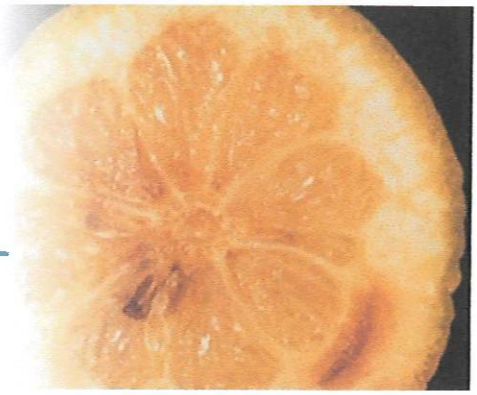


Response of potatoes to boron treatment

Attribute	Result
Yield increase above control	5% to 38% Median 11%, n=15 increase
Specific gravity (SG)	0,6% to 2% increase
Total soluble solids	7% to 51% increase
Dry matter	65% increase
Hardness	34% increase
Total acidity	19% increase
Ascorbic acid	2% to 20% increase
Starch	1% to 23% increase
Protein	71% increase
Reducing sugars	**5% to 8% decrease**
Non reducing sugars	4% to 8% decrease
Total sugars	5% to 12% decrease
Total phenols	**37% decrease**
Chip coloration	**42% decrease**



Citrus



General symptoms



Citrus response to boron treatment

Attribute	Result
Yield increase above control	2% to 280% increase Median = 16%, n = 10
Fruit drop	**20% reduction**
Juice content	3% to 4% increase
Total soluble solids	1% to 4% increase
Ascorbic acid	6% to 8% increase



Srivastava and Singh, 2005
Tariq et al. 2007
Hilal et al., 2017
Mattos et al., 2017
Wu et al., 2017
Zekri and Obreza, 2021
Yang et al., 2022

Table grapes



General symptoms

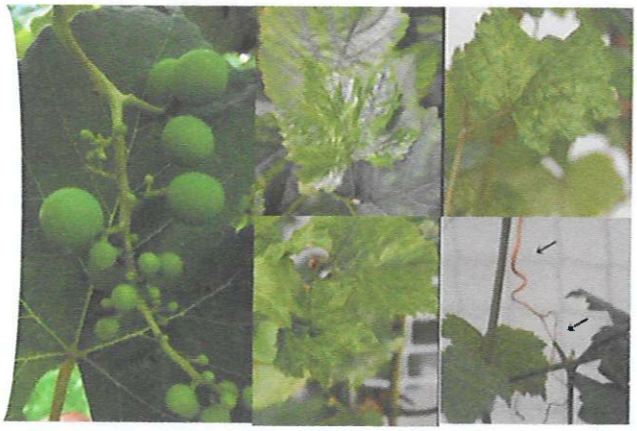


Table grape response to boron treatment

Attribute	Result
Yield increase above control	6% to 80% increase Median 14%, n=9
Bunch length	**7% to 8% increase**
Bunch weight	6% to 9% increase
Berry weight	25% to 30% increase
Berry firmness	**17% to 47% increase**
Berry diameter	7% to 9% increase
Fruit set	18% increase
Fruit weight	15% increase
Juice quantity	4% to 8% increase
pH	2% decrease to 40% increase
Titratable acidity	10% to 48% decrease
Ascorbic acid	51% to 56% increase
Total soluble solids	11% to 21% increase
Reducing sugars	13% to 38% increase
Non reducing sugars	50% to 97% increase
Total sugar	5% to 57% increase



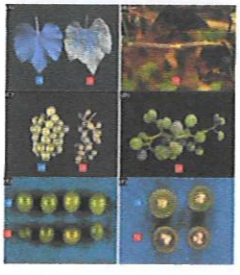
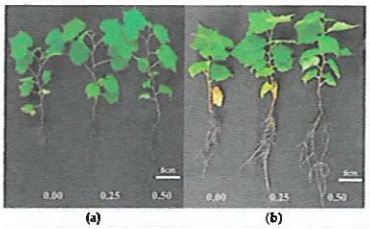


Table grape response to boron treatment (continued)

Attribute	Result
Chlorophyll A	27% to 31% increase
Chlorophyll B	57% to 73% increase
Flavour	41% to 57% increase
Texture	33% to 54% increase
Taste	45% to 54% increase
Market acceptance	41% to 50% increase



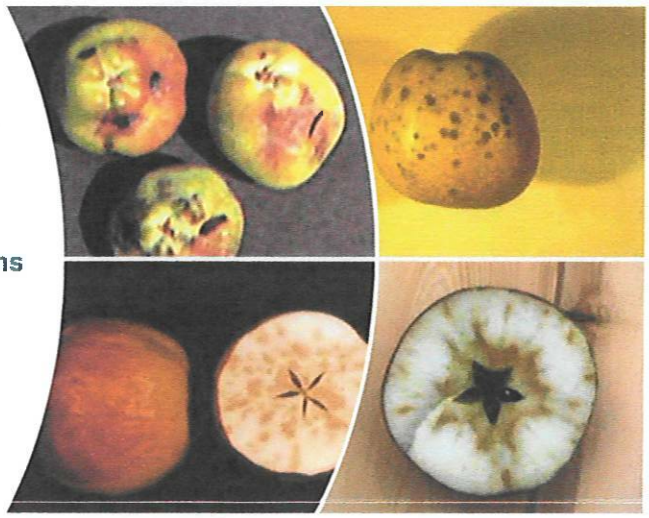
Growth status of two genotypes treated with 0.00, 0.25, and 0.50 mg L^{-1} B solution for 60 days: (a) 'Kishu-4'; (b) 'Crystal'

Akin and Kara, 2011
Batukaev et al., 2017
Swathi et al., 2019
Ali et al., 2022
Botelho et al., 2022
Wei et al. 2022

Apple



General symptoms



Response of apples to boron treatment

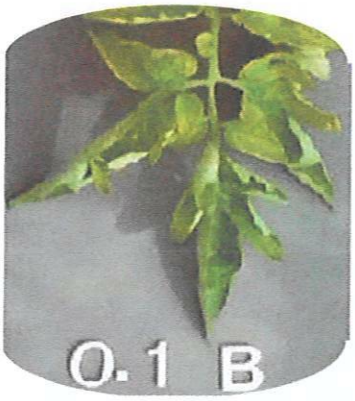
Attribute	Result
Yield increase above control	1% to 119% increase Median = 6%, n = 35
Fruit diameter	10% to 19% increase
Fruit set	18% increase
Fruit weight	15% increase
Titratable acidity	8% to 91% increase
Ascorbic acid	5% to 15% increase
Total soluble solids	2% to 24% increase
Total sugar	10% to 53% increase

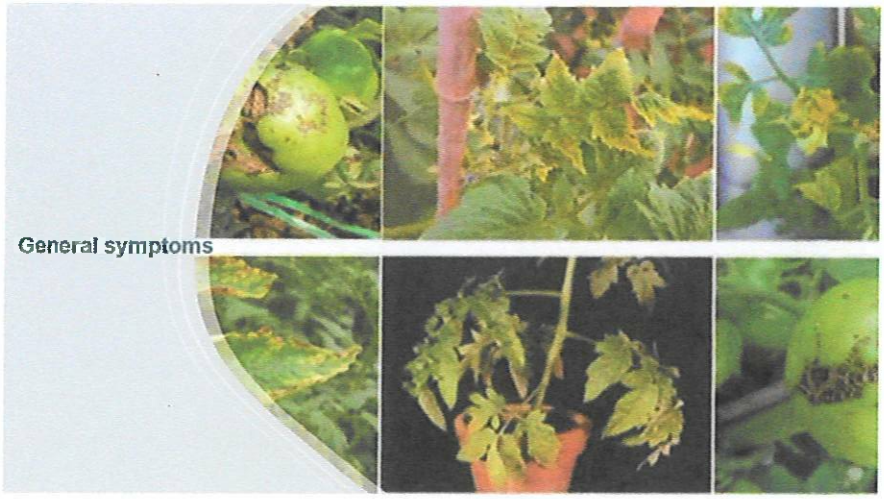
Świątdys, 1995
Wojcik et al., 2013
Sharma, 2016
Dar, 2017
Sofi et al., 2019
Rouf et al., 2029





Tomato



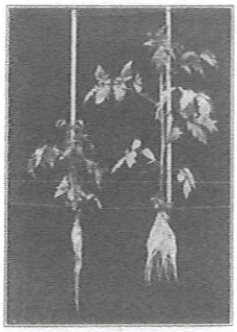


Response of tomato to boron treatment

Attribute	Result
Yield increase above control	1% to 4 fold increase Median = 36%, n = 22
Titratable acidity	27% to 49% increase
Ascorbic acid	24% to 91% increase
Total soluble solids	53% to 64% increase
Fruit set	30% to 56% increase
Shelf life	63% to 75% increase
Firmness	17% increase

Johnston and Dore, 1928
Francois, 1984
Davis and Lengnick, 2003
Davis et al., 2003
Naz et al., 2012
Bubaral et al., 2018
Dora Agritech, 2023
US Borax, 2023

Johnston & Dore, in Plant Physiology, 1928



Photograph showing boron deficient tomato plant (left) and one grown in a similar solution to which 0.55 ppm. boron as boric acid had been added (right).

Conclusion

- Boron as micronutrient plays a **prominent role in the nutrition (physiology) of the soil biome, plants, animals and humans**
- The chemistry, uptake, mobility, metabolism and management of boron as plant nutrient are **quite complex**
- **Boron, without doubt, is an essential micronutrient for plants.** Without it, dramatic **yield losses (median losses of between 5% and 20%)** may be expected
- Boron significantly influences many **quality parameters** of crops and impacts on aspects like **disease resistance, stress tolerance, WUE and NUE**
- The extent of **boron deficiency as micronutrient in crops, worldwide, is second only to zinc and the situation is worsening** with boron fertilizer demand increasing exponentially and supply dwindling




End