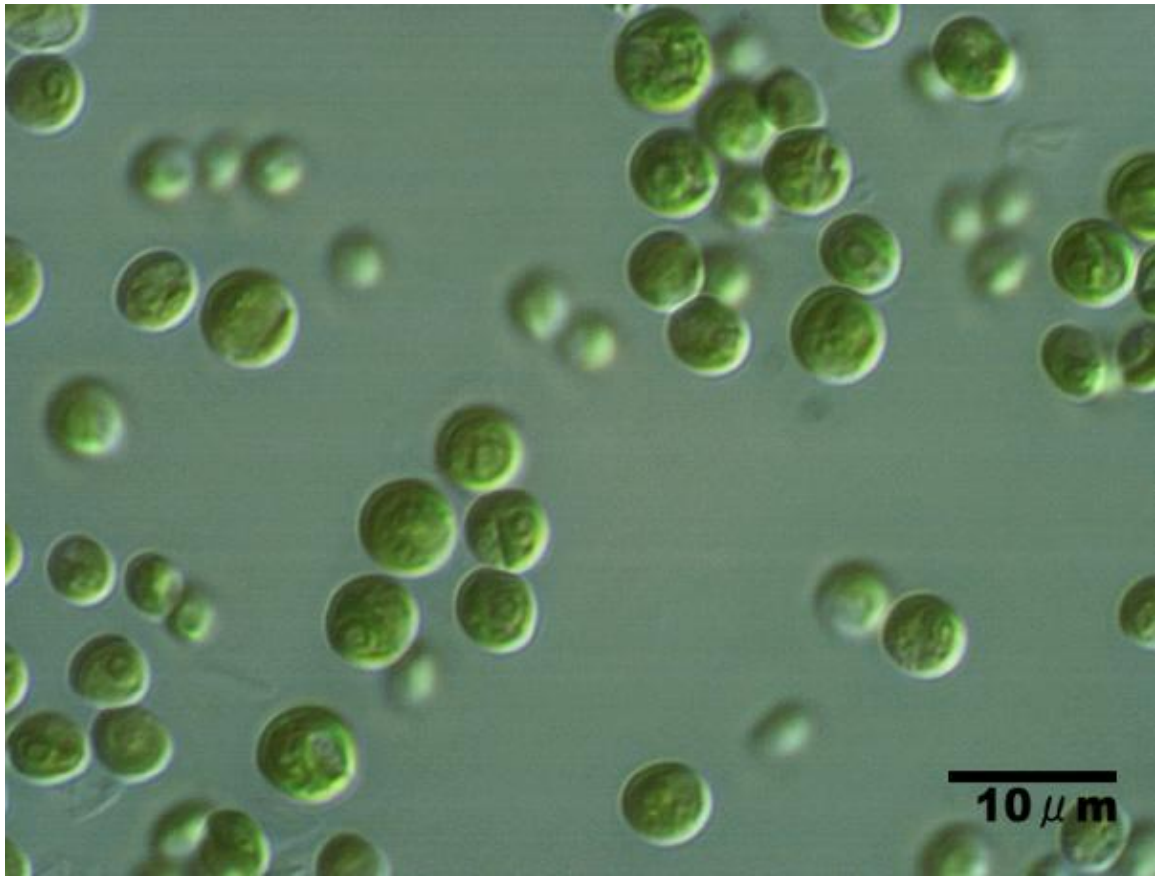
Chlorella vulgaris for Biostimulant formulations

A Rich, Natural, Sustainable & Circular source of Active Ingredients & Micronutrients

Chlorella species Taxonomy

Scientific Classification	
Domain:	Eukaryota
Kingdom:	Viridiplantae
Division:	Chlorophyta
Class:	Trebouxiophyceae
Order:	Chlorellales
Family:	Chlorellaceae
Genus:	***Chlorella***



What makes *Chlorella species* special

Aspect	Feature	Remarks
Evolutionary history	Several million, if not billions, of years old	Diverse genetics
Domain	Eukaryotic	Evolved, complex and hence biochemically rich
Structural organization	Uni-cellular	Single-celled & hence rich in composition
		All-in-one package with uniform composition
		High surface-area to mass ratio, with dense chlorophyll content & high photosynthesis rates
Reproduction	Primarily through cell division	Cells do not grow old, they simply divide into 2/3/4 and hence always actively growing
Evolution	Adaptive evolution in response to conditions	Accumulation of rich array of biomolecules to help mitigate various biotic & abiotic stresses
Growth rates	Among the highest in the plant kingdom	Pliable for mass production at high productivities with excellent biochemical composition

Chlorella vulgaris Bio-stimulant phytochemical profile

❑ Primary Metabolites

- **Proteins**: 45–60% (rich in essential amino acids: leucine, lysine, valine, methionine).
- **Lipids**: 10–20% (PUFAs such as α-linolenic acid, linoleic acid, palmitic acid).
- **Carbohydrates**: 15–25% (starch, β-glucans, rhamnose, mannose).

❑ Pigments:

- **Chlorophyll-a & b** (green pigments, photosynthetic efficiency).
- **Carotenoids** (lutein, β-carotene, zeaxanthin, astaxanthin traces).

❑ Secondary Metabolites (Bioactive Compounds)

- **Phenolics & Polyphenols**: antioxidant activity.
- **Flavonoids**: quercetin, kaempferol derivatives.
- **Alkaloids**: trace bioactive compounds.
- **Sterols**: ergosterol, stigmasterol.

❑ Vitamins & Cofactors

- **Water-soluble**: B-complex (B1, B2, B6, B12), Vitamin C.
- **Fat-soluble**: Vitamin A (from β-carotene), Vitamin E (α-tocopherol), Vitamin K.

❑ Minerals & Trace Elements

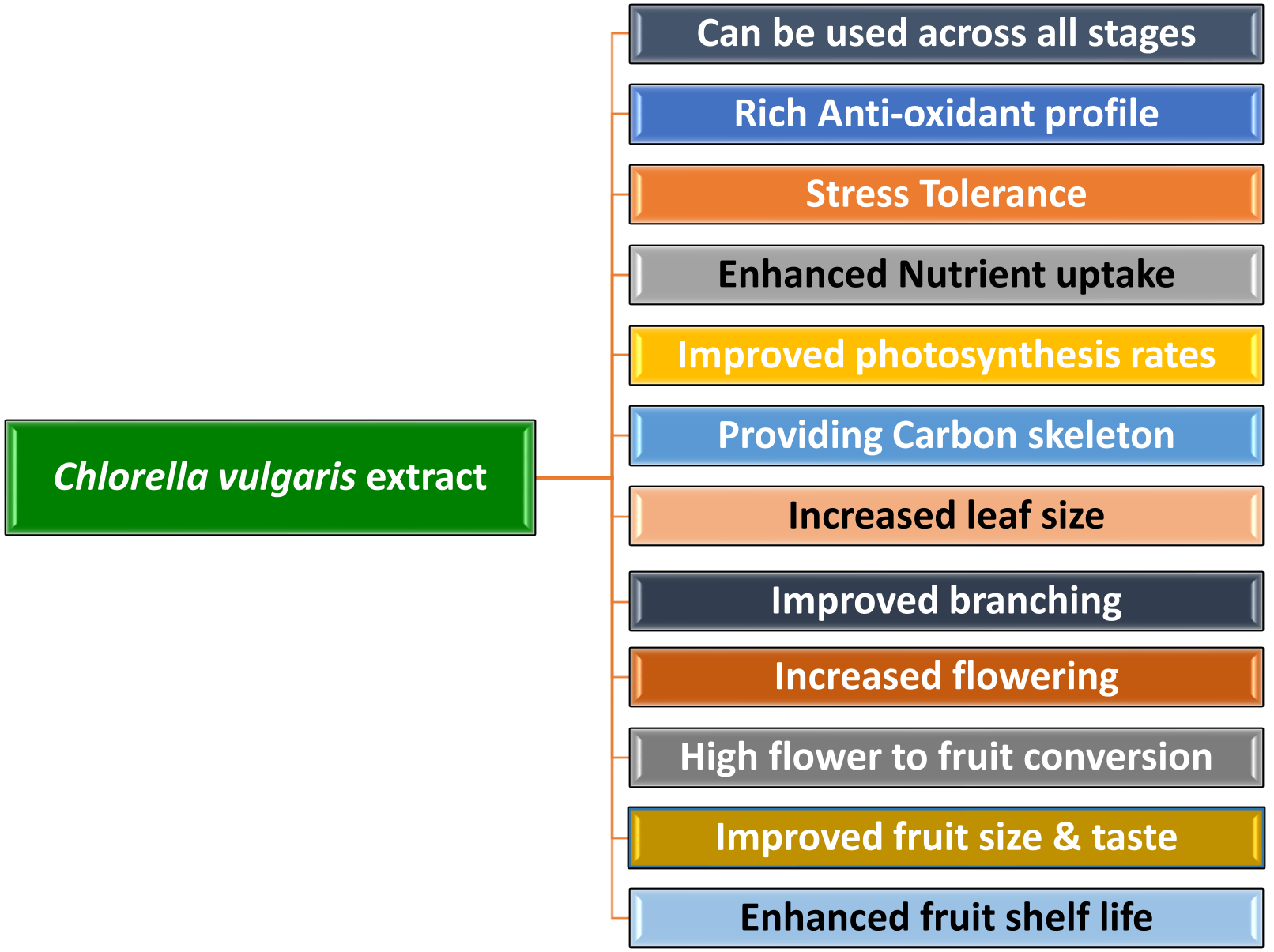
- **Macro-elements**: Ca, Mg, K, P, S.
- **Microelements**: Fe, Zn, Cu, Mn, Se.

❑ Phytohormones (Plant Growth Regulators)

- **Auxins** (indole-3-acetic acid, IAA).
- **Cytokinins** (zeatin, kinetin-like compounds).
- **Gibberellins** (GA-like compounds, promoting elongation).
- **Abscisic acid (ABA)** in trace amounts (stress regulation).

Chlorella vulgaris is a **rich cocktail of proteins, amino acids, pigments, vitamins, minerals, antioxidants, and plant hormones**, making it a powerful **biostimulant.**

Beneficials characteristics of *Chlorella vulgaris* for use in Biostimulant formulations



Effect of *Chlorella vulgaris* bio-stimulant during different stages of growth

❑ Rich Natural Composition

- Contains amino acids, proteins, vitamins (B-complex, C, E, K), minerals, phytohormones (auxins, cytokinins, gibberellins).
- Supplies bioactive compounds that stimulate plant metabolism and root development.

❑ Seed Germination & Early Growth

- Enhances seed germination percentage and seedling vigor.
- Promotes **root elongation** and stronger early establishment.
- Improves the germination rate under stress conditions.

❑ Vegetative Growth

- Boosts **chlorophyll synthesis** → greener, healthier leaves.
- Stimulates photosynthesis and biomass accumulation.
- Increases uptake of macro- and micronutrients.

❑ Reproductive Growth & Yield

- Enhances **flower initiation, fruit setting, and grain filling**.
- Reported to increase the yield in cereals, vegetables, and fruits.
- Improves crop quality (size, color, sugar content, nutritional profile).

❑ Stress Tolerance

- Rich in antioxidants (carotenoids, polyphenols) → protects plants from oxidative stress.
- Improves tolerance to **drought, salinity, and temperature stress**.
- Strengthens plant defence against pathogens (biotic stress).

❑ Soil & Microbial Benefits

- Stimulates beneficial soil microbes in the rhizosphere.
- Enhances organic matter mineralization and nutrient cycling.
- Improves soil fertility and health over time.

Application: It can be applied as a foliar spray, soil drench, or for seed treatment.

Antioxidant Benefits of *Chlorella vulgaris* for Crops

❑ Rich in Antioxidant Compounds

- Contains **carotenoids (lutein, β-carotene, astaxanthin)**, **phenolics**, **vitamins C & E**, and **chlorophyll**.
- These molecules scavenge **reactive oxygen species (ROS)** that accumulate under stress.

❑ Enhances Plant Stress Tolerance

- Reduces **lipid peroxidation** in plant cell membranes (protects leaf chlorophyll and structure).
- Helps crops maintain photosynthesis under heat, drought, or salinity.

❑ Boosts Enzymatic Antioxidants in Plants

- Stimulates activity of **superoxide dismutase (SOD)**, **catalase (CAT)**, and **peroxidase (POD)** in plants.
- These enzymes are natural defense shields against oxidative damage.

❑ Delays Senescence (Anti-aging effect)

- Antioxidants from chlorella reduce premature **leaf yellowing** and improve **flower/fruit retention**.

Net Effect of superior antioxidant profile: on stress tolerance: Improved yields & fruit quality by protecting from oxidative stress. Crops show **better biomass, flowering, and fruit quality** (higher sugar, pigment, and vitamin content).

Stress Tolerance Role of *Chlorella vulgaris* Bio-stimulant in Crops

❑ Drought & Water Stress

- Increases **osmolyte accumulation** (proline, sugars) that help plants retain water.
- Enhances **stomatal regulation** → better water-use efficiency.
- Protects chlorophyll and photosynthesis under dehydration.

❑ Salinity Stress

- Provides antioxidants and phytohormones (cytokinins, auxins) that reduce **Na^+ toxicity**.
- Improves uptake of essential nutrients (K^+, Ca^{2+}, Mg^{2+}).
- Boosts enzyme activities that detoxify **reactive oxygen species (ROS)** generated under salt stress.

❑ Heat & Temperature Stress

- Stimulates synthesis of **heat-shock proteins** and antioxidants.
- Maintains **membrane stability** and reduces lipid peroxidation.
- Improves survival and growth during heatwaves.

❑ Heavy Metal / Pollution Stress

- Chlorella cell walls bind heavy metals (Pb, Cd, As), reducing their toxic uptake by plants.
- Its antioxidants help neutralize stress induced by pollutants.

❑ Biotic Stress (Pests & Pathogens)

- Produces bioactive compounds that act as **elicitors of plant defence** (e.g., triggering phenolic pathways).
- Enhances systemic resistance → stronger plant immunity.

Net Effect on stress tolerance: All-round tolerance to several abiotic & biotic stresses through induction of superior biochemical pathways

How *Chlorella vulgaris* Bio-stimulant Improves Nutrient Uptake in Crops

❑ Root Growth Stimulation

• Chlorella contains **auxins, cytokinins, gibberellins, and indole-3-acetic acid (IAA)** which stimulate root elongation and branching.

• A stronger root system increases the **root surface area**, improving absorption of water and nutrients from the soil.

❑ Microbial Interaction in Rhizosphere

• Chlorella extracts act as a carbon source and stimulate **beneficial soil microbes** (PGPR, mycorrhizae, nitrogen-fixing bacteria).

• This improves **nutrient mineralization** and solubilization of phosphorus, potassium, and micronutrients.

❑ Organic Acids & Chelation

• Rich in **organic acids, peptides, and polysaccharides**, Chlorella helps **chelate micronutrients** (Fe, Zn, Mn, Cu).

• Chelation keeps nutrients soluble and available for root uptake even in poor or alkaline soils.

❑ Photosynthetic Pigments & Metabolites

• Chlorella pigments & vitamins act as natural enhancers of plant metabolism.

• Higher photosynthetic efficiency drives more demand for nutrients and optimizes their assimilation.

❑ Improved Stress Tolerance → Better Uptake

• Under salinity, drought, or heavy metal stress, plants often struggle to take up nutrients.

• Chlorella's antioxidants (polyphenols, carotenoids, superoxide dismutase activity) reduce oxidative stress, allowing plants to **maintain root function and nutrient absorption**.

❑ Enhanced Soil Nutrient Cycling

• Chlorella biomass contributes **amino acids, peptides, and polysaccharides** that enrich soil organic matter.

• This improves **CEC (cation exchange capacity)** & nutrient retention in rhizosphere.

Net Effect on nutrient uptake: Improved root growth, bioavailability & reduced stress resulting in better nutrient uptake & heathier soils

How *Chlorella vulgaris* Bio-stimulant Improves Photosynthesis in Crops

❑ Supply of Photosynthetic Pigments

• Chlorella is rich in **chlorophyll a & b, carotenoids, and phycobiliproteins**.

• These compounds act as **natural pigment precursors**, boosting the chlorophyll content in crop leaves.

• More chlorophyll = stronger **light-harvesting capacity** → better CO_2 fixation.

❑ Stimulation of Plant Hormones

• Contains **auxins, cytokinins, and gibberellins**.

• Cytokinins **delay leaf senescence** and increase chlorophyll retention, prolonging the active photosynthetic period.

• Hormonal balance leads to **higher stomatal conductance** → improved CO_2 uptake.

❑ Enhanced Nutrient Uptake for Photosynthetic Machinery

• Improves uptake of **Mg (core of chlorophyll), Fe, Mn, Cu, and N** –

• Nitrogen boosts Rubisco activity → faster carbon fixation.

• Iron & manganese improve **electron transport** in photosystems I & II.

❑ Boosting Carbon Assimilation

• Chlorella metabolites (amino acids, peptides) act as **carbon skeletons**.

• Supports **Calvin cycle enzymes** for more efficient CO_2 conversion into sugars.

❑ Antioxidant Protection of Photosystems

• Rich in **polyphenols, carotenoids, superoxide dismutase, and glutathione-like molecules**.

• Protects chloroplasts from **ROS (reactive oxygen species)** under stress (heat, drought, salinity).

• This maintains the integrity of **PSII reaction centres** & improves light-use efficiency.

❑ Improved Water Use Efficiency

• By enhancing root development and osmolyte production, Chlorella helps crops maintain **turgor pressure**.

• Well-hydrated leaves keep **stomata open** → optimal CO_2 diffusion for photosynthesis.

Net Effect on Photosynthesis: Improved photosynthesis through optimum efficient carbon utilization & reduced photooxidative damage

How *Chlorella Vulgaris* Bio-stimulant Provides Carbon Skeletons

❑ Amino Acids & Peptides in Extracts

1. Chlorella extracts are rich in **glutamate, aspartate, alanine, glycine, and peptides**.
2. These molecules serve directly as **ready-to-use carbon skeletons** for crop metabolism.
3. Chlorella-derived amino acids act as **direct nitrogen sources**.
4. Used in building **Rubisco, chlorophyll-binding proteins, and electron transport enzymes**, which are vital for photosynthesis.

❑ Organic Acids & Carbohydrates

1. Contains **malic acid, citric acid, pyruvate, and sugars** that enter the **TCA cycle**.
2. This supports **energy metabolism** and provides precursors for biosynthetic pathways.

❑ Priming the Calvin Cycle

1. During photosynthesis, the Calvin cycle fixes CO_2 into 3-carbon sugars (triose phosphates).
2. Chlorella metabolites provide **supplementary intermediates** that keep the cycle running efficiently, ensuring more sugars are formed from each unit of CO_2.

⚡ Net Effect on Photosynthesis

- **Faster assimilation of CO_2** because intermediates don't run short.
- Enhanced **protein and enzyme synthesis** (since amino acids are available).
- Stronger **stress resilience** because plants don't have to break down their own reserves — they can use external carbon skeletons supplied by Chlorella.
- Higher **chlorophyll content** (from improved protein & Mg metabolism).
- Faster **enzyme regeneration** (Rubisco, PEP carboxylase, ATP synthase).
- Stronger **electron transport & CO_2 fixation**.
- Greater **growth & biomass accumulation**.

How *Chlorella vulgaris* Bio-stimulant Increases Leaf Size in Crops

❑ Hormonal Stimulation → Cell Division & Expansion

- Produces **auxins (IAA), cytokinins, and gibberellins ➔** larger, thicker & greener leaves
- **Auxins** stimulate **cell elongation** in leaf tissues.
- **Cytokinins** promote **cell division** in meristematic regions (leaf primordia).
- **Gibberellins** encourage overall leaf expansion by loosening cell walls.

❑ Enhanced Chlorophyll & Pigments

- Chlorella is rich in **chlorophyll a & b, carotenoids, and precursors**.
- Boosts **chloroplast development** and photosynthetic pigments in new leaves.
- More photosynthesis → more carbohydrates → fuels leaf tissue growth.

❑ Improved Nutrient Uptake

- Chelating compounds in Chlorella (organic acids, peptides) keep nutrients soluble.
- Ensures steady supply of **N (for proteins), Mg (for chlorophyll), Fe & Mn (for electron transport)**.
- These nutrients are critical for **leaf expansion and thickness**.

❑ Carbon Skeletons & Amino Acids

- Chlorella provides **ready-made amino acids & organic acids**, which act as **building blocks** for new leaf cells.
- This reduces the plant's metabolic burden and speeds up **leaf biomass accumulation**.

❑ Delayed Leaf Senescence

- **Cytokinins from Chlorella** slow down aging (senescence) of leaves.
- Longer lifespan → more sustained growth → overall **larger leaf surface area**.

❑ Stress Mitigation → Sustained Growth

- Antioxidants in Chlorella (polyphenols, carotenoids, SOD-like activity) protect leaves from **oxidative stress** (heat, drought, salinity).
- Protects **cell membranes and chloroplasts**, allowing uninterrupted **leaf expansion**.

Net Effect of Chlorella Biostimulant on Leaf Size: More cells + bigger cells (hormonal effect) + **Greener, thicker leaves** (pigment & nutrient effect) + **Higher leaf area index (LAI)** → stronger photosynthetic capacity → better yield.

How *Chlorella vulgaris* Bio-stimulant Improves Branching in Crops

❑ Cytokinins Promote Lateral Bud Growth

•Chlorella is rich in **cytokinins**, which:

- Stimulate **cell division** in dormant axillary buds.
- Break **apical dominance** (the strong control of the main shoot tip).
- Encourage **side branches** to grow actively.

❑ Auxin–Cytokinin Balance

•Normally, high **auxin (IAA)** from the main shoot tip suppresses branching.

•Chlorella biostimulant supplies **exogenous cytokinins** and balances auxin:cytokinin ratio.

•This **reduces apical dominance** and allows more **lateral shoots** to emerge.

❑ Gibberellins for Shoot Elongation

•Gibberellins in Chlorella help new lateral branches **elongate rapidly**, ensuring they become strong and photosynthetically active.

❑ Improved Nutrient Uptake & Transport

•Chlorella enhances absorption of **N, P, K, and micronutrients**.

•Adequate **nitrogen** is crucial for the development of **axillary buds and branches**.

•Better nutrient flow supports multiple shoots rather than just the main stem.

❑ Energy & Carbon Skeletons

•Amino acids and organic acids from Chlorella serve as **building blocks for new tissues**.

•This metabolic support allows plants to sustain **multiple growing points** at once.

❑ Stress Tolerance → Stronger Growth Points

•Antioxidants and osmoprotectants in Chlorella protect meristematic tissues from **oxidative and drought stress**.

•Keeps axillary buds alive and capable of sprouting into branches under suboptimal conditions.

Net Effect: More **lateral shoots and tillers;** Greater **leaf area index (LAI);** Higher **flowering sites & fruiting potential;** Stronger **plant architecture** → improved yield.

How *Chlorella vulgaris* Bio-stimulant Increases Flowering & Reduces Flower Drop

❑ Hormonal Regulation

• **Cytokinins & Gibberellins** → stimulate **floral bud initiation** and differentiation.

• **Auxins (IAA)** → help in **flower organ development** and strengthen pedicel (flower stalk) attachment.

• This hormonal balance ensures **more flowers are initiated and sustained**.

❑ Improved Nutrient Availability

• Chlorella enhances uptake of:

- **Boron & Calcium** → strengthen cell walls in tissues, preventing premature abscission.
- **Phosphorus & Potassium** → crucial for energy supply and flower opening.
- **Micronutrients (Zn, Fe, Mn, Cu)** → support pollen development and fertility.

❑ Boost in Photosynthesis → More Energy for Reproduction

• Increased chlorophyll & pigments → stronger photosynthesis.

• More carbohydrates available for **flower initiation-retention** instead of just vegetative growth.

❑ Reduction in Oxidative Stress

• Chlorella provides **antioxidants (carotenoids, polyphenols, SOD-like activity)**.

• Protects developing floral buds from **ROS damage** under stress (heat, drought, salinity).

• Ensures flowers are not aborted prematurely.

❑ Strengthening of Pedicel & Ovary

• Amino acids and peptides from Chlorella help build stronger **vascular tissues**.

• Better nutrient and water transport → flowers stay attached longer → **reduced flower drop**.

❑ Stress Mitigation During Critical Stages

• During high temperatures, water stress, or nutrient imbalance, plants usually shed flowers, whereas Chlorella improves **osmotic balance, hormonal stability, and nutrient supply**, allowing flowers to survive stress.

Net Effect: More flowers initiated (due to hormones + nutrients); **Fewer flowers dropped** (due to antioxidants, Ca/B, auxins); **Better fruit set** → ultimately **higher yield**.

How *Chlorella vulgaris* Bio-stimulant Reduces Time for Flower → Fruit Conversion

❑ Hormonal Balance for Faster Pollination & Fertilization

• **Cytokinins & gibberellins** from Chlorella speed up **ovary development** after fertilization.

•**Auxins (IAA)** promote **pollen tube growth and fertilized ovary expansion**, ensuring quicker transition to fruit.

•Result → **rapid fruit initiation** after flowering.

❑ Enhanced Nutrient Supply to Developing Ovary

•Chlorella improves uptake of **Boron, Calcium, Potassium, & Phosphorus**:

- **Boron** → pollen tube growth, fertilization success.
- **Calcium** → strong ovary cell walls, preventing abortion.
- **Potassium & Phosphorus** → energy and osmotic regulation for fruit set.

•This ensures flowers rapidly convert into strong, viable fruits.

❑ Boost in Carbohydrate Supply

•Chlorella increases **photosynthesis** (higher chlorophyll, better CO_2 fixation).

•Provides ready-made **sugars & carbon skeletons** (amino acids, organic acids).

•Extra energy flows directly to reproductive sinks (flowers/ovaries), accelerating fruit formation.

❑ Stress Protection During Transition

•Under stress (heat, drought, salinity), flowers often delay or abort fruiting.

•Chlorella's **antioxidants, osmoprotectants, and polyphenols** protect floral tissues and ovary, preventing delays.

•Helps the plant **commit resources quickly to fruit set**.

❑ Better Pedicel & Vascular Development

•Amino acids and peptides strengthen **vascular tissues** connecting flower to stem.

•Faster **nutrient and water flow** supports quick ovary swelling → fruit initiation.

Net Effect of Chlorella Biostimulant: Faster pollination & fertilization (hormones + boron), **Quicker ovary swelling** (auxins, nutrients, sugars); **Stronger sink strength** for flowers to turn into fruits; **Reduced time from flower → fruit set**, leading to **early harvests & higher yields**

How *Chlorella vulgaris* Bio-stimulant Increases Fruit Size & Taste

❑ Hormonal Regulation for Fruit Growth

• **Auxins & Gibberellins** from Chlorella stimulate **cell division and cell enlargement** in the fruit pericarp → bigger fruits.

• **Cytokinins** keep fruit cells metabolically active longer, extending the growth phase.

• Net effect → **larger fruit biomass**.

❑ Improved Nutrient Transport to Fruits

•Chlorella improves uptake and translocation of:

- **Potassium (K):** regulates sugar transport into fruits → bigger, sweeter fruits.
- **Calcium (Ca):** strengthens cell walls → firmer fruits with less cracking.
- **Boron (B):** helps in cell wall elasticity and fruit set.

•This ensures **continuous nutrient supply to developing fruits**, boosting size-taste.

❑ Boosted Photosynthesis → More Sugars for Fruits

•Chlorella enhances **chlorophyll content** and **CO_2 assimilation**.

•Provides extra **carbon skeletons & amino acids** as building blocks.

•More assimilates = higher **sugar accumulation in fruits**, improving sweetness

❑ Enhanced Organic Acids & Aroma Precursors

•Chlorella contains **organic acids (malic, citric, succinic)** which act as precursors for fruit acidity and flavor balance.

•Supports synthesis of **secondary metabolites** (phenolics, flavonoids, carotenoids), improving **taste, color, and aroma**.

❑ Antioxidants for Fruit Quality

•Carotenoids, polyphenols, and vitamins (A, C, E) from Chlorella protect fruits from oxidative stress.

•Leads to **better color development, shelf-life, and nutritional value**.

❑ Stress Reduction → Better Fruit Filling

•Under drought, salinity, or heat, plants often produce smaller, bland fruits.

•Chlorella's **osmo-protectants & antioxidants** ensure steady fruit filling → uniform size and improved taste.

Net Effects on Fruits: Bigger size: due to auxins, gibberellins, K, Ca, sugars; **Better taste:** due to sugars, organic acids, antioxidants, carotenoids; **Higher quality:** firmer texture, better color, longer shelf-life.

How *Chlorella vulgaris* Bio-stimulant Improves Shelf Life of Fruits

❑ Calcium & Boron Uptake → Stronger Cell Walls

• Chlorella improves absorption of **Ca and B**, which are critical for **cell wall and middle lamella stability**.

• Firmer cell walls = **less softening, cracking, and leakage** during storage.

• Fruits resist **mechanical damage and microbial infection** longer.

❑ Antioxidant Protection Against Senescence

• Rich in **carotenoids, polyphenols, vitamins (C, E), and SOD-like activity**.

• These reduce **oxidative stress** in harvested fruits, slowing down:

- Chlorophyll breakdown (delayed yellowing).
- Lipid peroxidation (slower softening).

• Result → **slower aging and ripening**.

❑ Improved Nutrient Status → Balanced Ripening

• Adequate **Potassium & Magnesium** ensure controlled sugar loading into fruits.

• Fruits mature **uniformly and more slowly**, reducing uneven ripening and spoilage.

❑ Stronger Cuticle & Epidermis

• Chlorella-derived **amino acids, peptides, and polysaccharides** improve fruit skin elasticity.

• Tougher peel → better barrier against **water loss and pathogens**.

❑ Delayed Ethylene Production

• By reducing plant stress and oxidative bursts, Chlorella lowers **ethylene overproduction** in fruits.

• Ethylene is the main hormone that accelerates ripening & senescence.

• Lower ethylene = **slower ripening = longer shelf life**.

❑ Stress Protection During Growth → Better Post-Harvest Quality

• Fruits grown under Chlorella biostimulant have stronger internal structure and higher antioxidant reserves.

• These reserves continue to protect fruits even **after harvest**.

Net Effects on Shelf Life: Firmer texture, less shrivelling; Reduced post-harvest losses; slower ripening and senescence; Longer market window for growers and traders

Comparison between *Chlorella V* and other bio-stimulants

Feature / Benefit	*Chlorella*	*Spirulina*	Seaweed Extracts	Humic Acids
Key Components	Proteins, amino acids, vitamins, phytohormones, antioxidants	High protein, phycocyanin, vitamins, minerals	Auxins, cytokinins, betaines, polysaccharides	Humic & fulvic acids, organic carbon
Growth Promotion	Enhances germination, root elongation, chlorophyll synthesis	Stimulates root and shoot growth, supports photosynthesis	Boosts flowering, fruit set, vegetative growth	Improves root structure, nutrient absorption
Stress Tolerance	High (antioxidants, pigments help against drought, salinity, heat)	Moderate (improves resilience via phycocyanin)	Moderate (mainly osmotic & salinity stress)	Moderate (mainly soil-related stress)
Soil & Microbial Health	Enhances beneficial microbes, nutrient cycling	Improves soil microbiota modestly	Improves soil-water balance slightly	Strongly improves soil fertility & CEC

Comparison between *Chlorella* and Spirulina

Feature / Parameter	*Chlorella*	*Spirulina*
Organism type	Eukaryotic green microalga (Chlorophyta)	Prokaryotic cyanobacterium (blue-green alga)
Cell wall	Rigid cellulose-rich wall → protects bioactives, but needs extraction/processing	Thin peptidoglycan wall → more readily digestible, easier release of compounds
Main pigments	Chlorophyll-a, Chlorophyll-b, carotenoids, lutein	Chlorophyll-a, phycocyanin (blue pigment), carotenoids
Proteins & peptides	45–55% dry weight; rich in growth-promoting peptides & amino acids	55–65% dry weight; high in phycobiliproteins with antioxidant roles
Vitamins	B-complex (esp. B12 analog), vitamin C, E, K, provitamin A	B-complex, vitamin E, provitamin A, some unique antioxidants
Phytohormones	High in auxins, cytokinins, gibberellins (well-documented plant growth stimulation)	Lower auxin/cytokinin content but has polyphenols and antioxidants for stress mitigation
Bio-stimulant effects on crops	• Improves germination & seedling vigor • Enhances root growth & nutrient uptake • Boosts chlorophyll synthesis & photosynthesis • Delays senescence (anti-stress hormones)	• Improves stress tolerance (drought, salinity, oxidative stress) • Enhances photosynthetic efficiency via phycocyanin • Provides nitrogen-rich proteins for soil microbes • Increases antioxidant defence in plants
Mode of action	Hormonal stimulation + Nutrient Chelation + Microbial interaction	Antioxidant protection + Nitrogen source + Osmo-protectants

Green *Chlorella vulgaris* for Sustainability & Circularity in Agriculture