NATIONAL GREENHOUSE MANUFACTURERS ASSOCIATION

NGMA

MEETING THE CHALLENGES OF TODAY'S HORTICULTURAL INDUSTRY

Greenhouse Standards

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RUTGERS

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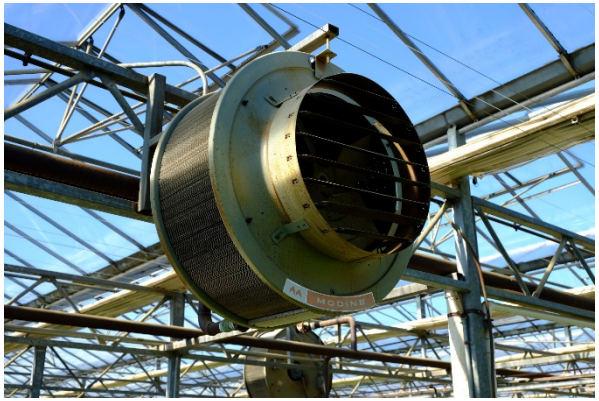
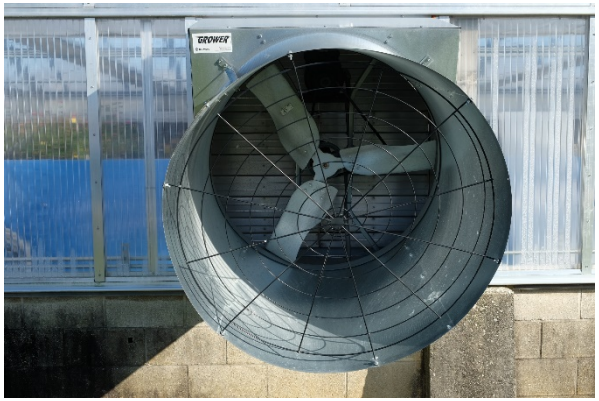
- What are standards?

- Documents that describe design & construction practices
- Documents that describe operational practices
- Written by knowledgeable stakeholders (volunteers)
- Vetted by a committee of experts (volunteers)
- Published by professional societies and organizations
- Used by designers, builders, operators, and regulators
- Can be useful resources for litigation
- Revised on a regular basis (often every 3-5 years)





- Why do we need standards?
  - Provide a starting point for designers
  - Improve efficiency of construction/installation
  - Improve operation/maintenance
  - Make life easier for parts/system suppliers
  - Provide assurances to the end-users
  - Provide guidance for building code officials
  - Serve as reference in case of disputes
  - Where appropriate, standards specifically address safety
  - Where appropriate, standards address efficiency and environmental impact

https://www.poblocki.com

- What are the challenges?
  - Greenhouse industry is diverse, and a niche market
  - Finding volunteers
  - Reaching consensus among experts
  - Keeping pace with new developments
  - Finding/developing independent data
  - Making sure standards are used (correctly)
  - Writing/revising standards can be a lengthy process

https://commons.wikimedia.org

- Role of the American National Standards Institute

  - Oversees the creation, promotion, and use of standards and norms
  - Accredits organizations that develop standards (e.g., ASABE)
  - Accredited organizations have to follow specific rules and procedures

ANSI

- International Organization for Standardization

- Independent NGO
- Headquartered in Geneva, Switzerland
- Members: 163 national standard organizations
- Published over 22,500 international standards
- Including standards on quality management and the environment (9001 and 14001, respectively)
- Does not certify companies complying with these standards
- Certification is done by third party certification bodies

- Useful (to you?) international standards

- DIN EN 13031-1: Greenhouses - Design and construction - Part 1: Commercial production greenhouses (EU)
- NEN 3859: Design and construction of greenhouses for commercial crop production (the Netherlands)
- Standards for Greenhouse Structures (Japan Greenhouse Horticulture Association)
- Korean standards (are working on updating wind loads)
- Chinese standards (solar greenhouses)

https://www.birmingham.ac.uk


WERNER
BRUTE

- US greenhouse design standards and processes

- International Code Council (e.g., building, fire, plumbing, mechanical)
- ASCE 7-10 (Minimum Design Loads for Buildings and Other Structures)
- Local/state building codes/regulations (That may have specific exclusions, exceptions or provisions for agriculture that either relax or tighten particular requirements)
- EPA (air, land, pesticides, water) and OSHA (worker safety & health)
- ANSI/ASABE EP460 (Design and Layout)
- ANSI/ASABE EP406 (Heating, Ventilating and Cooling)
- ASHRAE (Applications Handbook, Chapter 24)
- NGMA Standards and Guidelines

- *In order to get construction permits, engineering drawings have to be approved by the local zoning board. These drawings have to be verified and signed by a licensed professional engineer. In addition, a local code official has to review and approve the construction plans.*

- ASABE EP460 (Commercial Greenhouse Design and Layout)

- Design loads
  - Dead loads (building components, equipment)
  - Live loads (e.g., plants suspended from structure)
  - Wind loads
  - Snow loads
- Materials and methods of construction
  - Frame, covering materials, foundation
- Site selection and layout
  - Regulations, orientation, headhouse, drainage
- Interior layout
  - Growing systems, benches, material flow
- Utilities
  - Electricity, water, fuel source

Withdrawn

- ASABE EP406 (Heating, Ventilating and Cooling Greenhouses)
  - Heat loss calculations
  - Heating and air circulation systems
    - Hot water, hot air, bench and floor heating, polytube, HAF
  - Natural ventilation
  - Mechanical ventilation
  - Evaporative cooling
    - Pad and fan
    - Fogging
  - Heating and ventilation controls
  - Carbon dioxide enrichment
  - Cooling and venting small greenhouses

Withdrawn

- National Greenhouse Manufacturers Association
  - Standards and guidelines:
    - Curtain systems
    - Electrical designs
    - Environmental controls
    - Fire Safety
    - Glazing
    - Heating systems
    - Heat loss
    - Insect screening
    - Ventilation and cooling

- Additional standards/guidelines/references

  - Greenhouse Engineering (Aldrich and Bartok)
  - The Greenhouse Climate Control Handbook (ACME Corp.)
  - ASHRAE Applications Handbook
    - Chapt. 24 (Environmental Control for Animals & Plants)
  - Plant Growth Chamber Handbook (Langhans and Tibbitts, eds.)
  - ANSI/ASABE EP411: Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers

- International Committee for Controlled Environment Guidelines

  - Minimum guidelines for measuring and reporting environmental parameters for experiments on plants in growth rooms and chambers (2004)
  - Guidelines for measuring and reporting environmental parameters for experiments in plant tissue culture facilities (2008)
  - Guidelines for measuring and reporting environmental parameters for experiments in greenhouses (2015)

Additional considerations

Introduction

Conditions in controlled environment plant growth rooms and chambers (CE units) should be reported in detail for comparison of results and duplication of experiments. The minimum guidelines table, along with these notes, should help meet these aims, indicating a required, minimum amount of information that should be reported. They may also highlight parameters that could be important, but that may not have been considered for measurement.

Average measurements should be reported, including their temporal standard deviation (s.d.).

All sensors should be calibrated regularly according to manufacturer's procedures and suggested frequency.

Radiation

- Output of all electric radiation sources decreases with hours of operation e.g. for some fluorescent lamps output may drop 20% after the first five months of use.
- Irradiance varies significantly across the growing area in many CE units.
- Vertical radiation gradients occur in all CE units, depending on chamber size, lamp type, lamp distribution, and luminaire shape.
- Spectra from electric lamps generally differ from that of the sun. Unnatural red to far-red light ratios may affect morphogenesis in some plants and photomorphogenic effects should be considered when interpreting results.

Temperature

- Differences may exist between the temperatures of the air and plant, especially under high radiation loads.
- Older on-off control systems can result in as much as ±5°C variation from the set point temperature.
- A vertical temperature gradient occurs in most CE units, depending on airflow rates and other factors.

Atmospheric moisture

- Air humidity affects plants in CE units directly (via transpiration and gas exchange) and indirectly (via the plant's energy balance and physical and biological environment).
- Heating and cooling cycles lasting only 1 to 3 minutes can change absolute humidity by 1 to 2%, altering relative humidity by 20 to 40%.
- Air humidity is a challenging parameter to monitor, but is critical to plant water relations and infection by foliar pathogens. Relative humidity (RH) is acceptable for reporting humidity until CE units can control vapour pressure deficit (VPD), or portable instruments are available to measure and display VPD.

Carbon dioxide

- Carbon dioxide (CO_2) is probably the least controlled environmental parameter in CE studies. Unfortunately, too little or too much CO_2 is hard to detect until plants start to show specific symptoms.
- Small variations in CO_2 can affect plant growth and development significantly. People in or around CE units, and even greenhouses, can increase CO_2, as may motor vehicles, heating systems, and other nearby sources that produce CO_2.
- Few CE units manufactured today have CO_2 control or monitoring equipment installed as a standard feature. However, most do have some degree of ventilation or air exchange, and good air exchange can moderate CO_2 build-up or depletion.
- Even if a CE unit is well ventilated, it is important to remember that the surrounding area with which it exchanges air should also be well ventilated.

Experimental design issues

- Ideally, a single CE unit should be treated as a single replicate. True replication requires using multiple CE units, or repeating treatments in each unit with time, both expensive and time consuming options.
- Regular transfer of plants between CE units may be an alternative to avoid direct confounding of effects of an imposed environment with that of a CE unit.
- Repeating experiments in a CE unit with poorly controlled or monitored environmental parameters may lead to erroneous assumptions about treatment conditions and resulting data.

Example of a report suitable for publication

The experiment was conducted in a 3 m by 4 m growth room equipped with cool white fluorescent lamps (Model 830, Philips) mounted above a clear glass barrier, and an upward airflow distribution system using sufficient outdoor make-up air to provide ambient CO_2 conditions inside the room. The room air temperature was maintained at 25/20°C (s.d. ±2/1°C) during the light/dark period. The photosynthetically active radiation (PAR) at the top of the canopy was maintained at 400 µmol m^{-2} s^{-1} (s.d. ±10 µmol m^{-2} s^{-1}) during the 12-hour photoperiod. The relative humidity in the room was maintained at 70% (s.d. ±10%). The plants were grown in 1 L pots filled with a peat-vermiculite (2:1 volume ratio) mixture. The plants were hand watered daily with a freshly prepared nutrient solution (full strength Hoagland, pH 6).

International Committee for
Controlled Environment Guidelines

Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

Sponsored by and published for the UK Controlled Environment Users' Group, the North American Committee on Controlled Environment Technology and Use (NCR-101), and the Australasian Controlled Environment Working Group

March 2004

Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

International Committee for Controlled Environment Guidelines

Parameter to measure		Units [1]	Where to measure	When to measure	What to report
Radiation	**Photosynthetically active radiation (PAR)** [2]	µmol m^{-2} s^{-1}	Top of plant canopy in centre of growing area	At start and end, and every 2 weeks of the experiment	Average and standard deviation. Radiation source (type, model, and manufacturer)
and	**Photoperiod**	h			Duration of light and dark periods
Temperature	**Air**	°C	Top of plant canopy in centre of growing area	Daily during each light and dark period, at least 1 hour after light/dark change	Average and standard deviation
	Liquid culture	°C	Within solution under plants	As above for air temperature	Average and standard deviation
Atmospheric moisture	**Water vapour pressure deficit (VPD)**	kPa	Top of plant canopy in centre of growing area	Daily during each light and dark period, at least 1 hour after light/dark change	Average and standard deviation
or	**Relative humidity (RH)**	%	As above for VPD	As above fpr VPD	Average and standard deviation
Carbon dioxide [3]		µmol mol^{-1}	Top of plant canopy	At least hourly	Average and standard deviation
Air velocity [3]		m s^{-1}	At one or more representative canopy locations	At least once during the experiment	Average and standard deviation
Watering		litre (L)		Daily	Frequency, amount and type of water added
pH	**Liquid culture**	pH	In the bulk solution	Before and after pH correction	Average and standard deviation
Electrical conductivity (EC) [3]	**Liquid culture**	S m^{-1}	In the bulk solution	Before and after EC correction	Average and standard deviation
Substrate				At start of the experiment	Type and volume per container, components of soil-less substrate, container dimensions
Nutrition	**Solid media**	mol kg^{-1} (dry)		When added or replenished	Nutrients and their form added to soil media
	Liquid culture	mmol L^{-1}		Daily, or when replenished	Ionic concentration in initial and added solution. Aeration if any. Volume of initial solution
Room or chamber properties	**Specifications**				Floor area. Manufacturer and model if available
	Barrier beneath lamps				Indicate if present and its composition
	Air flow				Indicate whether up, down or horizontal

1 Report in other multiples or sub-multiples of indicated units if more convenient.

2 Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies, and manufacturers of quantum sensors. When diurnal PAR is ramped, integrals should be reported, e.g. in mol m^{-2} d^{-1}.

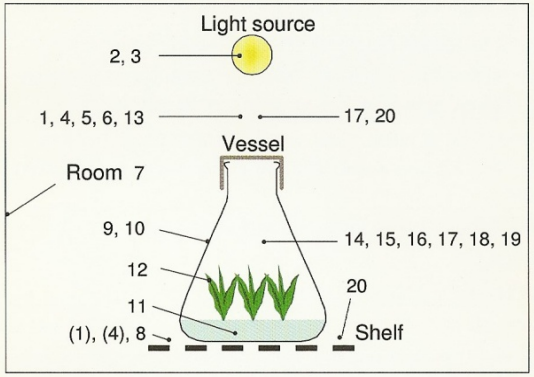
3 This parameter should be reported if records are available and always when it is a variable under investigation. For more information, consult the detailed guidelines published as ANSI/ASAE Engineering Practice EP411.4 (2002) 'Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers'. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

Introduction to guidelines

Tissue culture is a very significant tool for plant propagation and biotechnology and is a research technique for plant physiology and molecular biology. Facilities vary from low-tech equipment through off-the-shelf incubators to state-of-the-art suites of cabinets and rooms. In all cases, accurate environmental records are essential to standardise and maximise growth of cultures and to facilitate valid replication of experiments between different facilities.

The primary critical parameters common to most plant tissue culture facilities can be monitored and recorded relatively easily. The Table (over page) gives guidance on how to monitor and record these primary parameters, most of which ideally should be monitored at the location of the cultures (see Figure below). Facilities with automatic control systems usually measure temperature at the air re-circulation intake, which can differ significantly from that above a shelf. If several shelves are used in an experiment, then each shelf should be monitored.

Where to measure parameters



Key to Figure:

	Primary parameters		*Specialist parameters*
1.	Radiation	14.	Air temperature
2.	Light source - properties	15.	Atmospheric moisture
3.	Photoperiod	16.	Radiation
4.	Air temperature	17.	Spectral distribution of radiation
5.	Atmospheric moisture	18.	CO_2 concentration
6.	Air circulation	19.	Air exchange rate of vessels
7.	Room - properties	20.	Air velocity
8.	Shelf - properties	**Notes:**	
9.	Vessel - properties	Shelf level = as close as possible to	
10.	Vessel - alignment	top of shelf. Vessel level = above but	
11.	Culture medium	as close as possible to top of vessel.	
12.	Number of explants	Specialist parameters 14 to 19 are	
13.	CO_2 concentration	measured inside a vessel. () = optional	

Many research facilities have more elaborate recording equipment, or may be able to record a wider range of experimental parameters. The real environment of a tissue culture is inside the vessel. The most advanced facilities may have equipment available to carry out extremely detailed and technically difficult measurements inside vessels, including spectral distribution of radiation. The thirteen primary parameters and the seven most important specialist environmental parameters are identified and the location of their measurement is illustrated (see Figure). For details on the specialist parameters and their interactions with primary parameters see Fujiwara and Kozai (1995) [1]. If specialist parameters are measured they should be reported.

How to report your experimental conditions

Here is an example of a report suitable for publication:

"The experiment was conducted in a walk-in growth room (model, manufacturer) (11.2 m² floor area and 2.1 m ceiling height), with horizontal air circulation through perforated sidewalls and four stacked steel-mesh shelves (24 m² total shelf space). Sufficient outdoor make-up air was provided to maintain ambient CO_2 concentrations in the room. Cool white fluorescent lamps (model, manufacturer) mounted 40 cm above each shelf provided an average photosynthetically active radiation (PAR) of 50 (s.d. ±7) µmol m^{-2} s^{-1} above the culture vessels during the 16-h photoperiod. Air temperature above the culture vessels was 25/20 (s.d. ±1)°C during the light/dark period. Relative humidity above the culture vessels was 67 (s.d. ±10)%.

Ten plantlets were cultured in 200 mL glass Erlenmeyer flasks sealed with translucent plastic film. Each flask contained 40 mL of medium with Murashige and Skoog (1962) basal components, 30 g L^{-1} sucrose, 5 g L^{-1} of activated charcoal and 8 g L^{-1} agar. The pH of the medium was adjusted to 5.8. The flasks were in a single layer on each shelf with sufficient spacing to allow adequate air movement around each flask. No environmental parameters were recorded inside the flasks."

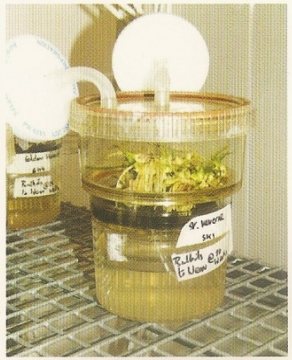
[1] Fujiwara, K. and Kozai, T. (1995) Physical microenvironment and its effects p. 319-369. In: J. Aitken-Christie, T. Kozai and M.A.L. Smith (eds) Automation and Environmental Control in Plant Tissue Culture, Kluwer Academic Publishers, Dordrecht, Netherlands.

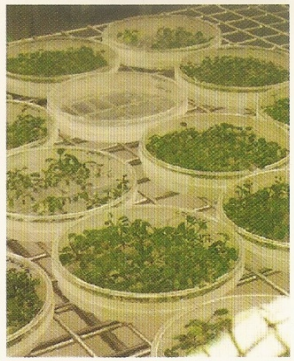
International Committee for Controlled Environment Guidelines

Guidelines for Measuring and Reporting Environmental Parameters for Experiments in Plant Tissue Culture Facilities

Sponsored by and published for the UK Controlled Environment Users' Group, the North American Committee on Controlled Environment Technology and Use (NCERA-101), and the Australasian Controlled Environment Working Group

March 2008





Measuring and Reporting Environmental Parameters for Experiments in Plant Tissue Culture Facilities: Table of Primary Parameters

International Committee for Controlled Environment Guidelines

What to measure	Units	Where to measure	When to measure	What to report
Radiation (PAR[1])	µmol m^{-2} s^{-1}	a) At vessel level, at uniform height throughout. (See Figure)	At start of experiment, and every 4 weeks [2]	Mean and standard deviation. Radiation sources (type, model and manufacturer, and distance from shelf)
		b) Optional, at shelf level, at centre of empty shelf [3]	As above	As above
Photoperiod	h		At start of experiment	Duration of light and dark periods
Air temperature	°C	a) At vessel level Location of sensor is crucial, and should be independent of the facility's temperature control sensor	Daily during each light and dark period, at least 1 hour after light/dark changeovers	Mean and standard deviation for light and dark periods
		b) Optional, at shelf level, at centre of shelf, outside container	As above	As above
Atmospheric moisture (relative humidity or vapour pressure deficit)	% or kPa	At vessel level and independently of the facility's humidity control sensor	Daily during each light and dark period, at least 1 hour after light/dark changeovers	Mean and standard deviation for light and dark periods
Air circulation		At vessel level	At start of experiment	Record whether perforated shelves, walls, ceiling, floor or ducts, and horizontal or vertical flow. Record source of fresh air
Room or cabinet properties			At start of experiment	Size (floor area m^2, ceiling height m) and type (walk in/reach in) Manufacturer and model if available, indicate if it has special features e.g. rotating shelves, light reflectors, bottom cooling of shelves
Shelf properties			At start of experiment	Area (m^2), type (solid or mesh, steel, wood or transparent), number (stacked, not stacked) and construction. Note if shelves are bottom cooled by air or water
Vessel specifications (It is appreciated that a range of vessels may be in use)			At start of experiment	Types (flasks, dishes, bottles, jars) and materials (glass, plastic) Size/volume (mL) Closure type and additional seal or vent
Vessel alignment		On each shelf	At start of experiment	Number of vessels and number of layers (if vessels are stacked) per shelf
Culture medium			At start of experiment	Solid, gel, or liquid (or combinations). Type and make of gelling agent. pH Volume per vessel (mL) Mineral composition (macro- and micro-nutrients) Carbon source, growth regulators, vitamins and their concentrations; also whether activated carbon and other additional substrates are in use
Number of explants		In each vessel	At start of experiment	Initial number of explants
Atmospheric CO_2 concentration	µmol mol^{-1}	At vessel level, at centre of shelf	Daily but only if CO_2 enrichment is installed within facility	Mean and standard deviation

1 Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies and manufacturers of quantum sensors

2 Fluorescent lamp efficiency declines significantly within weeks of installation and gradually thereafter and such lamps therefore require a regular monitoring and replacement programme

3 If lamps are arranged at the back of the shelf rather than above the shelf this should be stated and PAR measured at the back and the front of an empty shelf

- Greenhouse Guidelines content
  - Compliance and quality assurance
  - Definitions
  - Instruments and sensors (Table 1)
  - Parameters to monitor and report (Table 2)
    - Radiation
    - Temperature
    - Gases (including water vapor)
    - Liquid water
    - Nutrients
    - Structures, growing and control systems
  - Reporting example
  - Bibliography

- Greenhouse Guidelines Table 1: Instruments and sensors for measurement and their calibration

What to measure	Units	Measured by	Precision of instrument[2]	Accuracy of reading[2]	Calibrated by and when
Radiation (PAR[1])	µmol m^{-2} s^{-1}	Quantum sensor	±1%	±10%	Comparison with a reference sensor or against a standard quartz-halogen lamp traceable to a (inter)national standard (e.g. US NIST). Once per annum.
Radiation (Net)	W m^{-2}	Net radiometer	±2%	±5%	Comparison with a reference meter or in a temperature controlled calibration chamber capable of evaluating both short and long wavebands. Once per annum.
Radiation (Spectral)	µmol m^{-2} s^{-1} nm^{-1}	Spectroradiometer	±1%	±5%	Comparison with a reference meter or against a standard source of radiation (e.g. ASTM G138-06). Once per annum.
Irradiance (Solar)	W m^{-2}	Pyranometer	±1%	±5%	Comparison with a reference meter or against a standard source (traceable to the World Radiometric Reference) in an integrating sphere. Once per annum.
Radiation (Integral)	MJ m^{-2} d^{-1} or mol m^{-2} d^{-1}	Calculated from accumulated radiation data	-	-	-

[1]Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies and manufacturers of quantum sensors.

[2]Precision is how close the measured values are to each other. Accuracy is how close a measured value is to the actual (true) value.

Continued →

• Greenhouse Guidelines Table 1: Continued

What to measure	Units	Measured by	Precision of instrument[2]	Accuracy of reading[2]	Calibrated by and when
Air temperature	°C	RTD, thermocouple or thermistor (shaded and aspirated in air with speed ≥ 3 m s^{-1})	±0.1°C	±0.2°C	Comparison with a reference thermometer (e.g. traceable against US NIST) by placing in melting crushed ice and boiling distilled water. Once per annum.
Substrate temperature	°C	RTD, thermocouple or thermistor (ensure good contact with substrate)	±0.1°C	±0.2°C	As above.
Surface temperature	°C	Infrared temperature sensor, fine wire thermocouple	±0.1°C	±0.2°C	Infrared sensor: Comparison with a reference surface thermometer mounted on the same surface within the field of view of the infrared sensor. Thermocouple: as above.
Atmospheric moisture: relative humidity or vapour pressure deficit (VPD)	% or kPa	Capacitance, dewpoint sensor, psychrometer, or IRGA (infrared gas analyser)	Relative humidity: ±2% Dewpoint temp.: ±0.1°C VPD: ±0.3 kPa	±5% ±0.5°C ±0.5 kPa	Humidity generator; unsaturated salt solution calibration standards (35% and 80 % RH). Once per annum.
Air speed	m s^{-1}	Anemometer (range 0.1 - 15.0 m s^{-1})	±2%	±5%	Wind tunnel. Once per annum.
pH		pH probe (range 3 – 10)	±0.1 pH	±0.1 pH	Standard solutions. Before every measurement, or weekly in continuous measurement applications.
Electrical conductivity (EC)	S m^{-1}	Electrical conductivity meter	±3%	±5%	As above.
Dissolved oxygen	mg L^{-1}	Dissolved oxygen meter (maintain adequate solution flow rate and ensure temperature compensation)	±3%	±5%	As above.
Atmospheric CO_2 concentration	µmol mol^{-1}	Silicon based NDIR (non-dispersive infrared) sensor as part of an IRGA (infrared gas analyser)	±1%	±3%	Certified calibration gases for low and high end of the measurement range, and/or precision gas mixing instrument. Once per week.

[1]Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies and manufacturers of quantum sensors.

[2]Precision is how close the measured values are to each other. Accuracy is how close a measured value is to the actual (true) value.

• Greenhouse Guidelines Table 2: Primary Parameters – Minimum Set

What to measure	Units	Where to measure	When to measure	What to report
Air temperature	°C	At canopy level, in centre of growing area. Location of sensor is crucial, and should be independent of the greenhouse temperature control sensor. Include another sensor for outside temperature.	Preferably continuous, but at least hourly.	Mean and standard deviation for light and dark periods. Number of locations (preferably more than one).
Substrate temperature	°C	Inside plant container for solid and liquid substrates.	As above.	As above.
Radiation (PAR[1])	µmol m^{-2} s^{-1}	At top of canopy, in centre of growing area.	Preferably continuous, but at least hourly.	Mean and standard deviation. Number of measurement locations (preferably more than one). When used, supplementary radiation sources (type, model and manufacturer, distribution, energy consumption, conversion efficiency), and their duration of operation.
Photoperiod	h		Daily or when conditions change.	Duration of light period (including any night interruption).
Atmospheric moisture: relative humidity or vapour pressure deficit (VPD)	%, or kPa	At canopy level, in centre of growing area and independently of the greenhouse humidity control sensor.	Preferably continuous, but at least hourly.	Mean and standard deviation for light and dark periods. Number of locations (preferably more than one).
Atmospheric CO_2 concentration[2]	µmol mol^{-1}	At canopy level, at a representative location.	Preferably continuously, but at least hourly if CO_2 enrichment is used.	Mean and standard deviation. Number of measurement points and their location relative to the plant canopy.
pH		In root zone environment, or in nutrient solution directly applied to the root zone environment.	Preferably continuous, but at least hourly.	Mean and standard deviation. Location of measurement(s).
Electrical conductivity (EC)	S m^{-1}	In root zone environment, or in nutrient solution directly applied to the root zone environment.	Preferably continuous, but at least hourly.	Mean and standard deviation. Location of measurement(s).
Nutrition - liquid media	mmol L^{-1}		Daily or when replenished.	Ionic concentration in added solution. Frequency of additions. Aeration if any.
Nutrition - solid media	mol kg^{-1} (dry)		When added or replenished.	Nutrients and their form added to soil media. Frequency of additions.
Watering	Litre (L)	Growing system.	At start of experiment and when changed.	Frequency, amount, duration and type of water added per unit area or per plant. Mean and standard deviation. Type of irrigation system.
Plant alignment		On bench/floor/hanging system.	At start of experiment and when conditions change.	Number of plants per unit area and number of respacings or relocations.
Greenhouse properties		Greenhouse	At start of experiment.	Latitude and longitude. Orientation of long axis relative to compass North. Size (floor area m^2, growing area m^{-2}, gutter height m, peak height m), type (free-standing, gutter connected), shape (curved roof, peaked roof). Manufacturer and model if available, indicate if it has special features (e.g. type of glazing material, ventilation system, energy/shade curtain).

• Greenhouse Guidelines Table 2: Primary Parameters – Additional Parameters

What to measure[2]	Units	Where to measure	When to measure	What to report
Surface temperature	°C	Plant tissue: pointed at canopy or individual leaf surface; Greenhouse: pointed at structural surface	Preferably continuous, but at least hourly.	Mean and standard deviation. Location and orientation of the sensor. Distance of the sensor to the surface measured. Field of view of the sensor.
Radiation (Net)	W m^{-2}	At top of canopy, in centre of growing area.	As above.	Mean and standard deviation. If measured, also report solar radiation so that (net) long wave radiation can be determined.
Radiation (Spectral)	µmol m^{-2} s^{-1} nm^{-1}	As above and/or where of interest (e.g. within the canopy).	As often as practical.	Mean and standard deviation. Absolute or relative contribution of a specific wavelength or waveband to the overall radiation.
Irradiance (Solar)	W m^{-2}	Outside (unobstructed) and/or inside (at top of canopy, in centre of growing area).	Preferably continuous, but at least hourly.	Mean and standard deviation. When possible, calculate (average) transmission of radiation through the greenhouse cover.
Radiation (Integral)	MJ m^{-2} d^{-1} or mol m^{-2} d^{-1}	Calculated from accumulated data.	Continuously during the measurement interval.	Accumulated (typically daily) values. Relative contributions of supplementary and solar radiation to (daily) integral.
Air circulation	m s^{-1}	At canopy level.	At start of experiment and more frequently if conditions change.	Mean and standard deviation. Design of circulation system. Predominant direction of flow. Number of measurement points and their location relative to the plant canopy. Report whether open or closed greenhouse.
Substrate water content Volumetric or gravimetric water content, or matric potential	%, or kPa	Substrate	Daily	Mean and standard deviation. Number of measurement locations.
Dissolved oxygen	mg L^{-1}	In root zone environment, or in nutrient solution directly applied to the root zone environment	Preferably continuous, but at least hourly	Mean and standard deviation. Location of measurement(s)

[1]Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies and manufacturers of quantum sensors.

[2]Report if records are available, and always when it is a variable under investigation.

- Plant lighting standards

ASABE (ES-311 Committee):

S640: Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms)

S642: Recommended Methods of Measurements and Testing for LED Radiation Products for Plant Growth and Development
(any combination of LED components; lamp characteristics and long term behavior)

X644: Performance Measures of Electromagnetic Radiation Systems for Plants
(not for individual lamps)

- Other lighting standards and guides

UL:

8800: Outline of Investigation for Horticultural Lighting Equipment (Safety)

DOE:

Report: Energy Savings Potential of SSL in Horticultural Applications

DLC (represents power companies):

Horticultural Lighting Specification Development (Metrics for Rebates)

IES:

RP27.1-15: Recommended Practice for Photobiological Safety for Lamps and Lamp Systems – General Requirements

- Personal observations about standards

- For various reasons, standards are not freely accessible
- This does not help widespread adoption
- Shelved ASABE standards (406, 460) should be revived
- NGMA members should get more involved or even take leadership
- Academia can be a great partner, but can’t do it alone
- It’s a thankless job, but with important impacts
- A rising tide lifts all boats (but all need to be aboard…)

- Commercial versus institutional greenhouses
  - Both types of projects can benefit from standards
  - Specific differences can be addressed in standards

- Concluding remarks

- Standards are not static documents
- The more input, the better the standard will be
- Input from diverse stakeholders is crucial
- Standards are very useful across the entire industry
- Standards can enhance dialogue among stakeholders
- Standards are great educational tools
- Effort is required to write & update standards
- Without your participation, standards with a positive impact on your business are not guaranteed
- If standard development seems like a daunting task, consider developing guides/manuals/check lists, etc. and make them freely available (and update them regularly)
- Build teams to work on standard development

Thank You!!!

Questions?

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