Pros and Cons of Plasma Agriculture: A Current View

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Pankaj Attri, Masataka Okumura, Kazunori Koga
Kyushu University

1. Demand for environment friendly agricultural productivity enhancement
2. Remarkable plasma effects
3. Summary

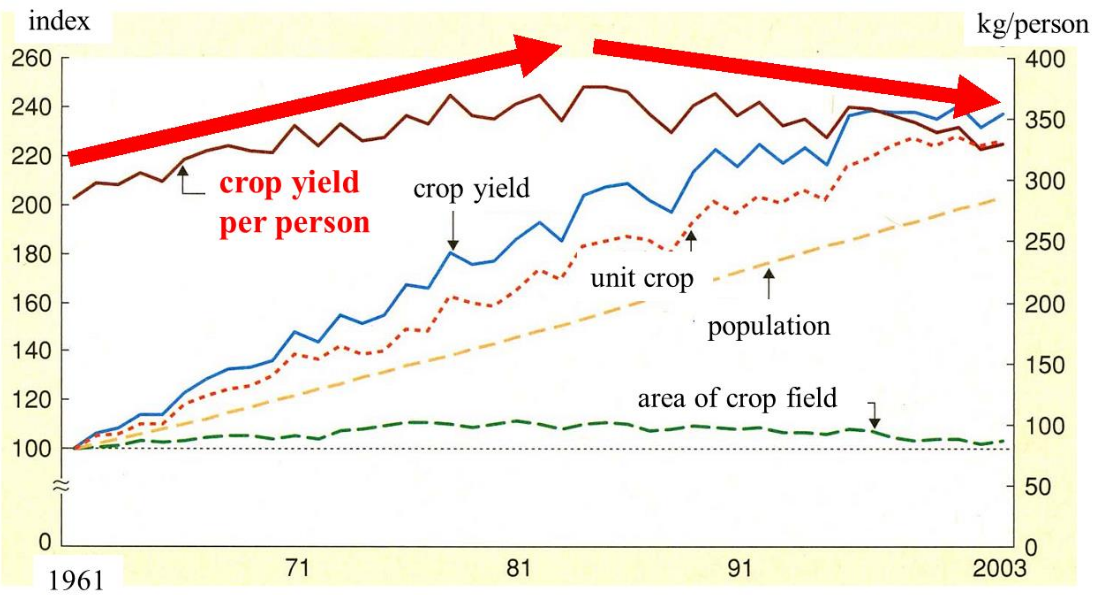
Plasma scientists optimize plant growth and yield

Researchers are fine-tuning the application of plasma to agriculture to speed up germination and help plants grow strong

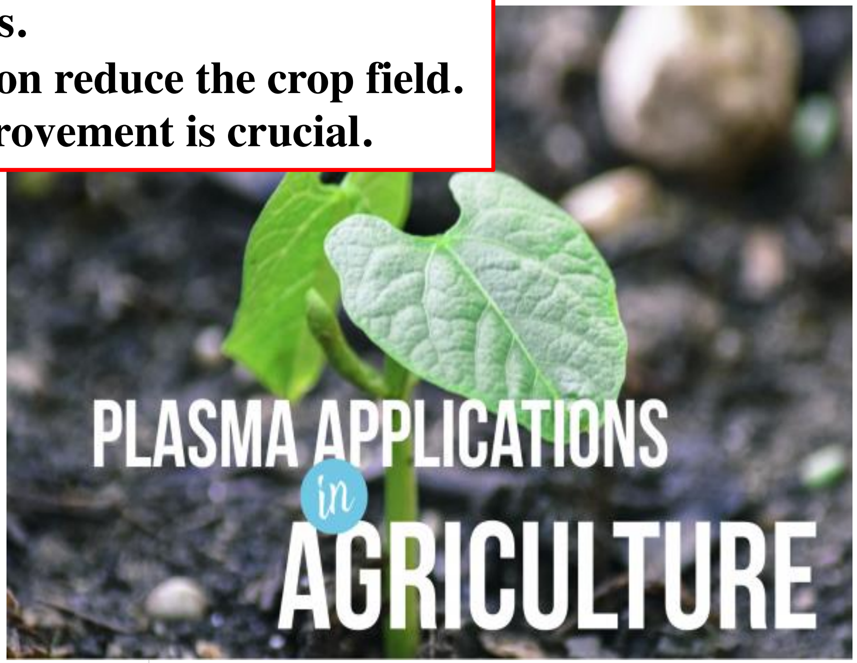
AMERICAN PHYSICAL SOCIETY

Crop yield per person tends to decrease since 1980's.
Global warming, excessive irrigation and fertilization reduce the crop field.
Environment friendly technology to crop yield improvement is crucial.

■ Trends of grain productivity (1961 = 100)



Ref: The state of food and agriculture



https://en.kfwiki.org/wiki/Plasma_Applications_in_Agriculture

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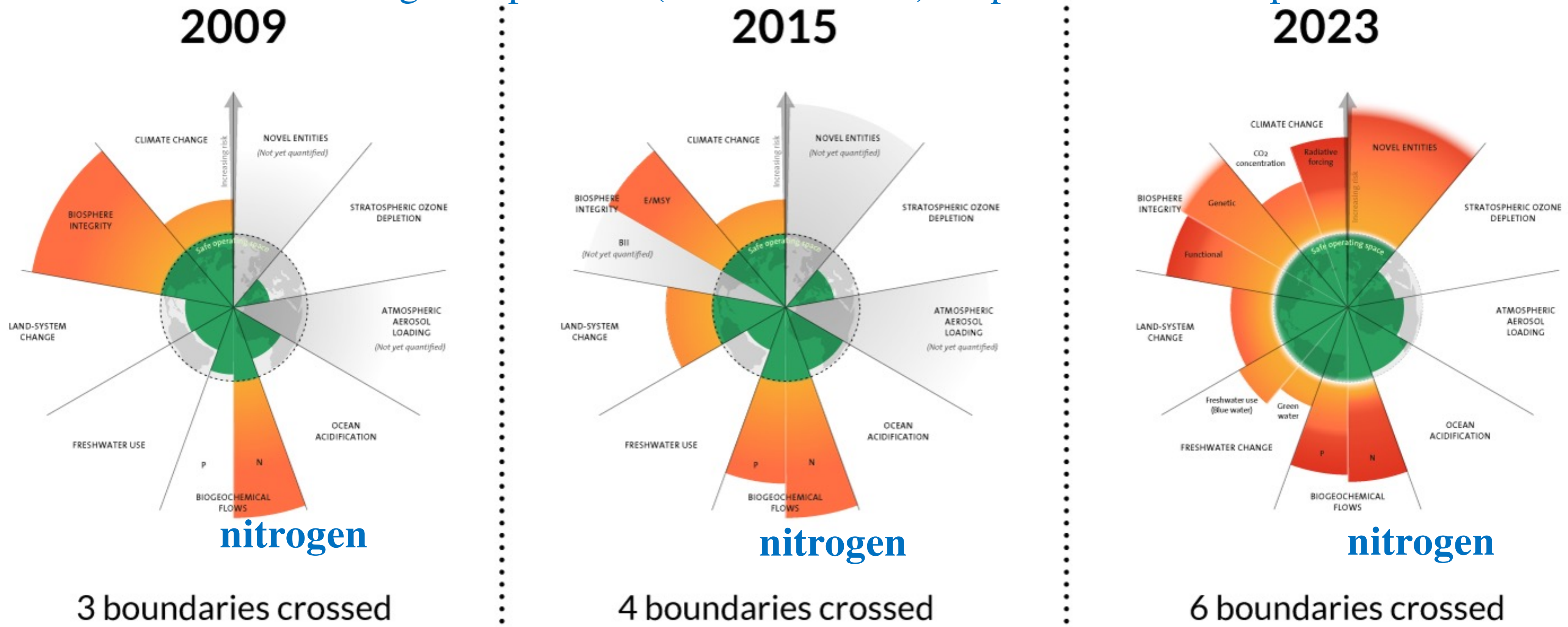
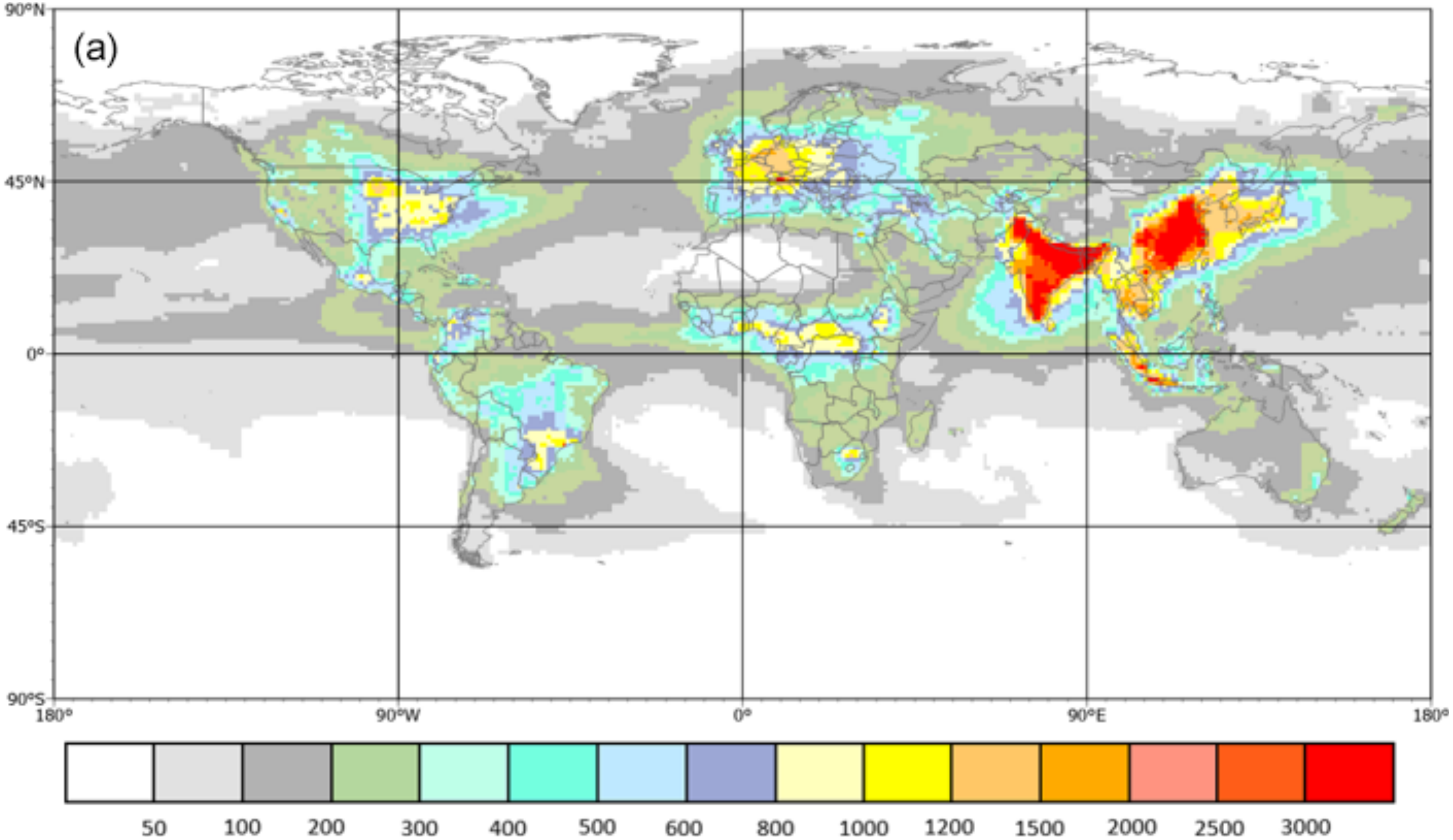
Planetary boundaries are a framework to describe limits to the impacts of human activities on the Earth system. Beyond these limits, the environment may not be able to self-regulate anymore. Crossing a planetary boundary comes at the risk of abrupt environmental change.

Artificial nitrogen deposition (Harbour Bosch) surpasses natural deposition.

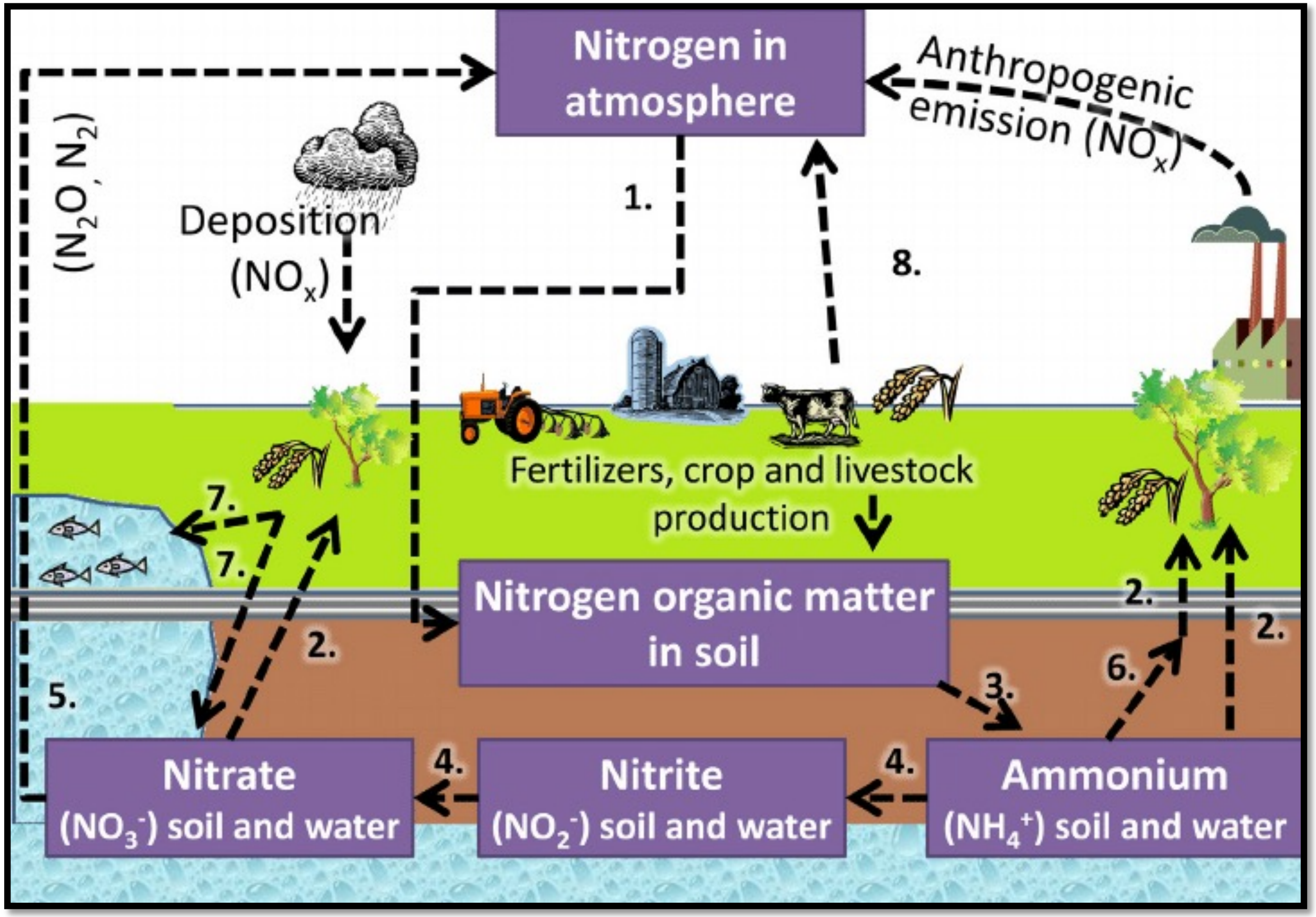


J. Rockström, et al., Nature. 461 (2009): 4726. K. Richardson, et al., Science Advances. 9 (2023): eadh2458.

China and India have super-heavy artificial nitrogen deposition.
EU, USA and Japan also have heavy artificial nitrogen deposition.



Nitrogen cycle



Nitrogen chemical fertilizer
fast-acting property
50% goes to plant growth,
50% goes to ground water.

Organic fertilizer
slow-acting property
Less nitrogen content
C/N > 15 ==➔ < 7 is good.

Plasma irradiated organic fertilizer
Fast & slow-acting property
Tune C/N by adding N content
On-site treatment
Reduction of nitrogen usage 1/10
for the same growth rate

https://www.researchgate.net/figure/The-nitrogen-cycle-1-uptake-of-nitrogen-by-plants-from-the-atmosphere-2-uptake-of_fig1_263329333

Classification : Fertilizer Market

- **Fertilizers are broadly divided into chemical fertilizers and organic fertilizers. Although chemical fertilizers currently occupy the majority of the market, the scale of organic fertilizers is expected to grow at a high rate in the future.**

Comparison : chemical fertilizers / organic fertilizers

	Chemical fertilizers	Organic fertilizers
Ingredients/Method of production	■ Chemical synthesis using inorganic substances that exist in nature such as ores and nitrogen gas in the air as raw materials	■ Produced from natural raw materials such as livestock manure, garbage, and human excrement
Market size (2021)	■ Approximately 93% (approximately $170 billion) of the entire fertilizer market	■ Approximately 7% (approximately $10 billion) of the entire fertilizer market
Market growth (2021-2030)	■ Expected to trend at a CAGR of around 2.8%	■ Expected to trend at a CAGR of around 12.0%
Availability Cost-effectiveness	■ Easy to procure raw materials ■ Cost-effective due to high nutrient concentration	■ Raw materials are more difficult to obtain than chemical fertilizers, and extraction methods are limited. ■ More expensive than chemical fertilizers
Ease of use	■ Consistent quality and various forms such as pellets ■ It is easy to adjust the amount used because the nutritional components can be accurately grasped ■ Immediate effect is high, but the fertilizer effect does not last for some	■ Organic fertilizers that have not been composted take time to fertilize ■ Inconsistent quality, depending on the type of raw material
Environmental impact	■ Continuous use can easily disrupt soil ecosystems and quality, potentially reducing soil fertility. ■ Potential loss of large amounts of nutrients through runoff and leaching	■ Maintain and promote healthy soil ecosystems during drought ■ Low amounts of nutrients that can be lost through runoff or leaching

（出所） 各種資料を基にMURCにて作成

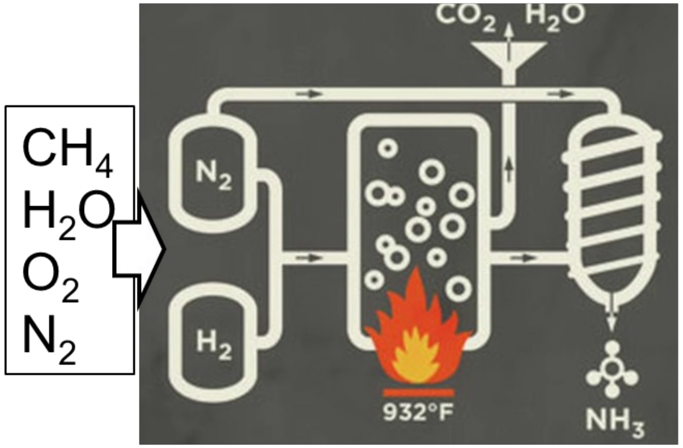
■ **Estimated market size of nitrogen organic fertilizer is approximately €5.6 billion.**

		Global Fertilizer Market : About €126 billion			
		Primary Macronutrients			Other
		Nitrogen	Phosphoric acid	Potassium	
Market Share		66% of the market	8% of the market	25% of the market	1% of the market
Chemical fertilizer	93%	**€77.2 billion**	**€9.1 billion**	**€29.5 billion**	**€1.4 billion**
Organic fertilizer	7%	**€5.6 billion** **Target market**	**€0.7 billion**	**€2.1 billion**	

Source: Research Dive, Verified Market Research data, Revised by university

Comparison between conventional process and plasma process

Conventional tech.: Haber-Bosch process



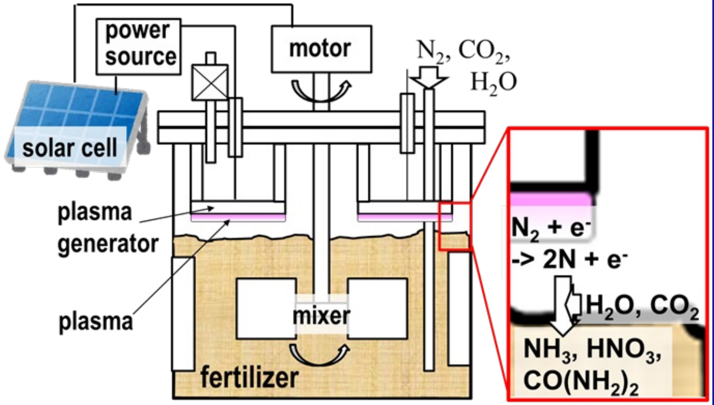
Disadvantages:

1. Uses of CH_4.
2. Uses of fossil fuel.
3. Greenhouse gas (GHG) emission.

Haber-Bosch (1200°C, 500 ATM)

$3CH_4 + 3O_2 + 2N_2 \rightarrow \mathbf{4NH_3} + 3CO_2$

Our solution: Plasma process

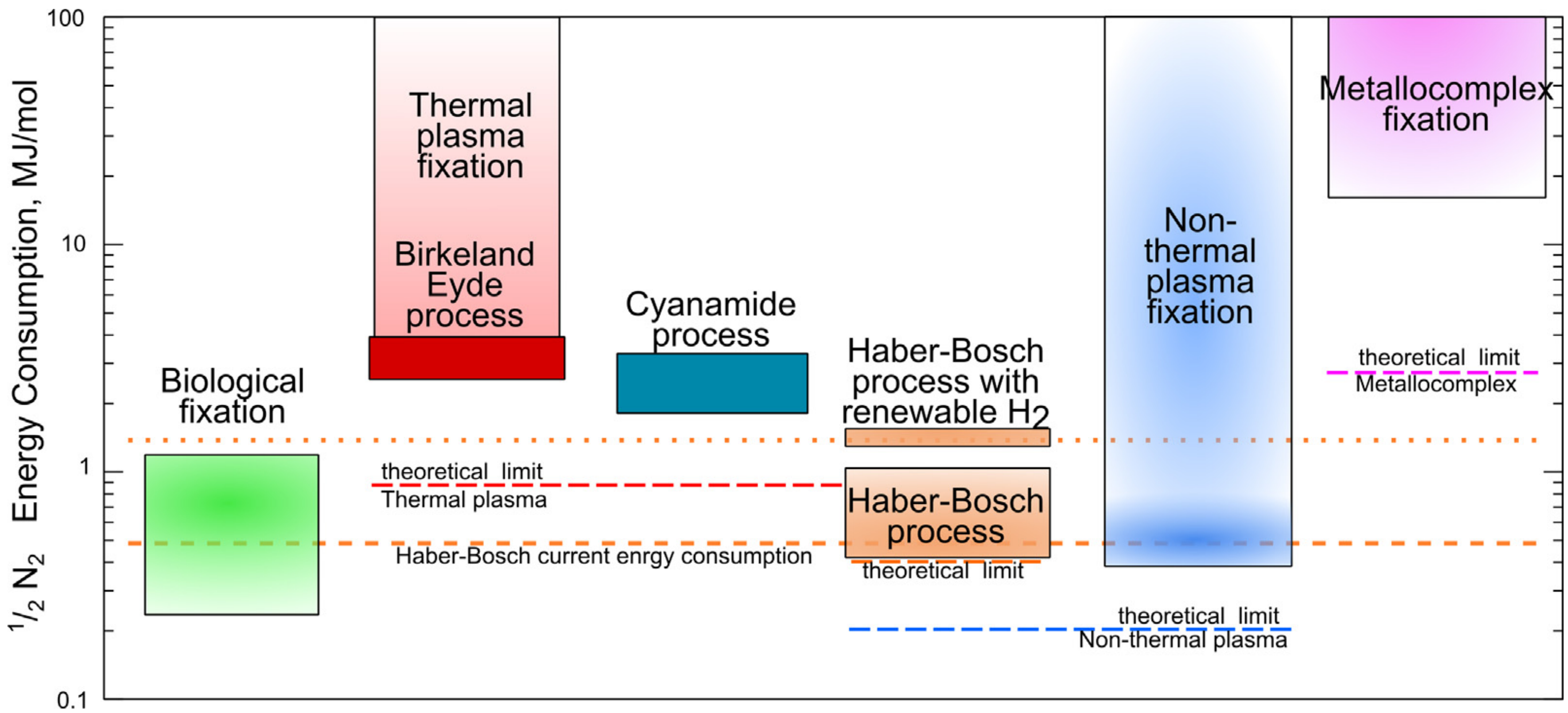


Advantages:

1. Only N_2 and water.
2. Uses of electricity.
3. Quite low GHG emission.
4. Better energy efficiency.
5. On-site N-fixation.

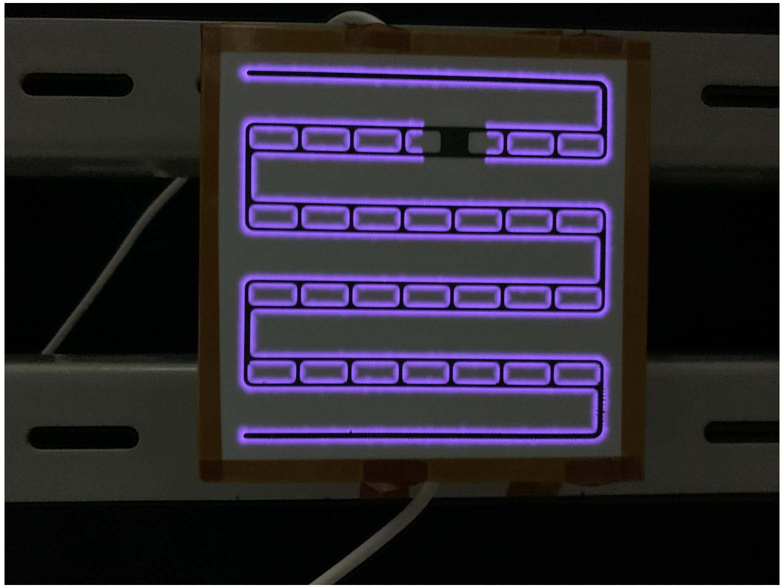
Energy consumption for nitrogen fixation

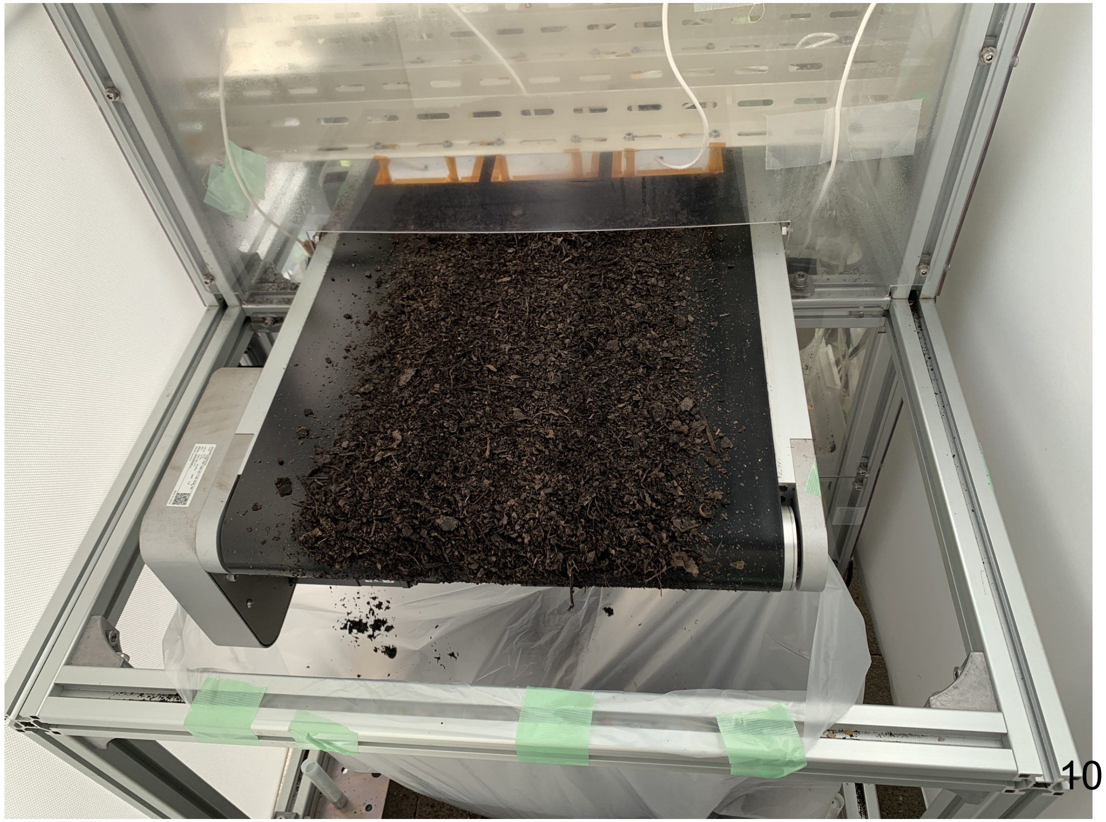
1. Food produced with nitrogen fertilizers feeds 50% of the world's population
2. Harber-Bosch accounts for 2% of global energy consumption and 1% of CO_2 emissions
3. Nitrogen fixation using low-temperature plasma consumes theoretically the least amount of energy
4. Energy consumption can be reduced by as much as 60% from the current Harber-Bosch



N. Cherkasov et al., Chemical Engineering and Processing 90 (2015) 24–33.

Air-DBD Reactor Used to fix nitrogen in leaf mold





Mass of reactive species in plant soil after plasma treatment.

	Control leaf mold	Plasma treated leaf mold	Plant leaf + commerical ammonium fertilzier (0.5 gm)
NO_2^- (g), Nitrite	0.0001	0.0010	0.0001
NO_3^- (g) , Nitrate	0.0088	0.0224	0.0092
NH_4^+ (g), Ammonium	0.0017	0.0111	0.0173

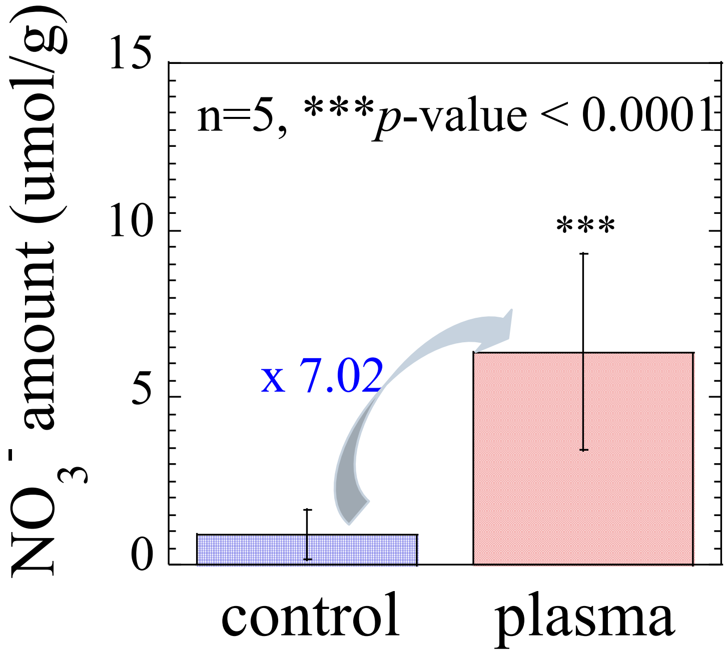
Germination of Radish sprouts is 85-95% in plasma treated leaves whereas it is 50-65 % in plant leaves without plasma treatment

The **energy consumption** (EC) for **total N-fixation** was 12 MJ/mol.

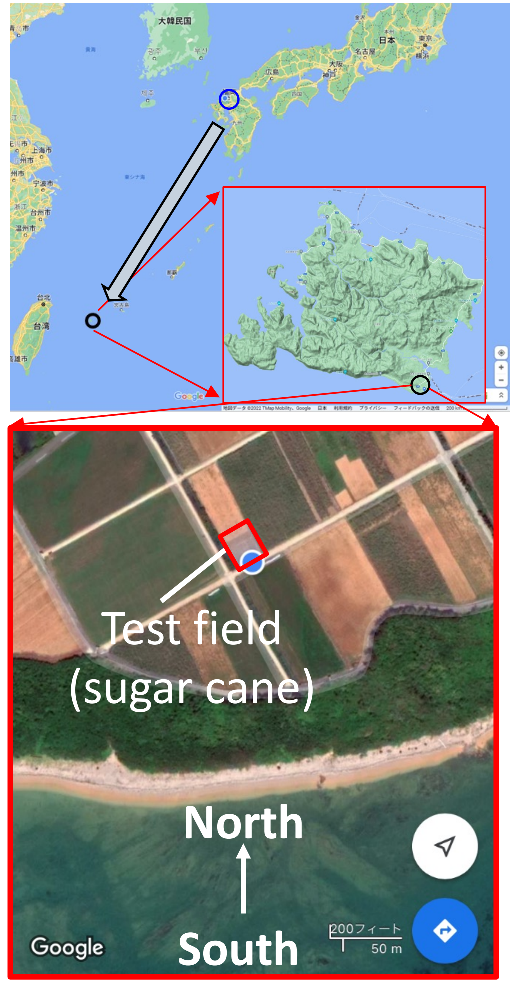
Theoretical limit is 0.2 MJ/mol. EC of Harbar-Bosch is 0.5 MJ/mol

P. Attri, et al., **RSC Advances, 2021**, 11, 28521.

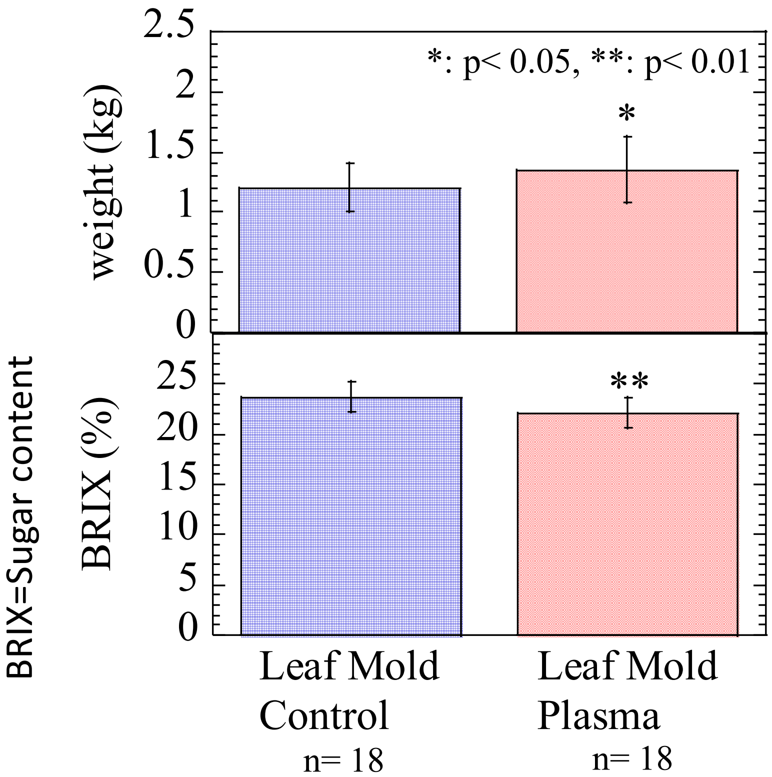
■ **NO_3^- amount in plasma-irradiated leaf mold is 7 times higher than that without plasma (control).**



Transport from Kyushu university, Fukuoka to Iriomote island, Okinawa



Harvest yield for plasma is 7% higher than that for control.



Estimated profit increase at the present: €490-/ha

$$(harvest\ yeild: HY) \equiv (weight) \times (BRIX)$$

HY_control= 0.28 (=1.2 x 0.237)
HY_plasma= 0.30 (=1.4 x 0.221)

*assumption: efficiency of extraction from fresh weight to juice weight is same.

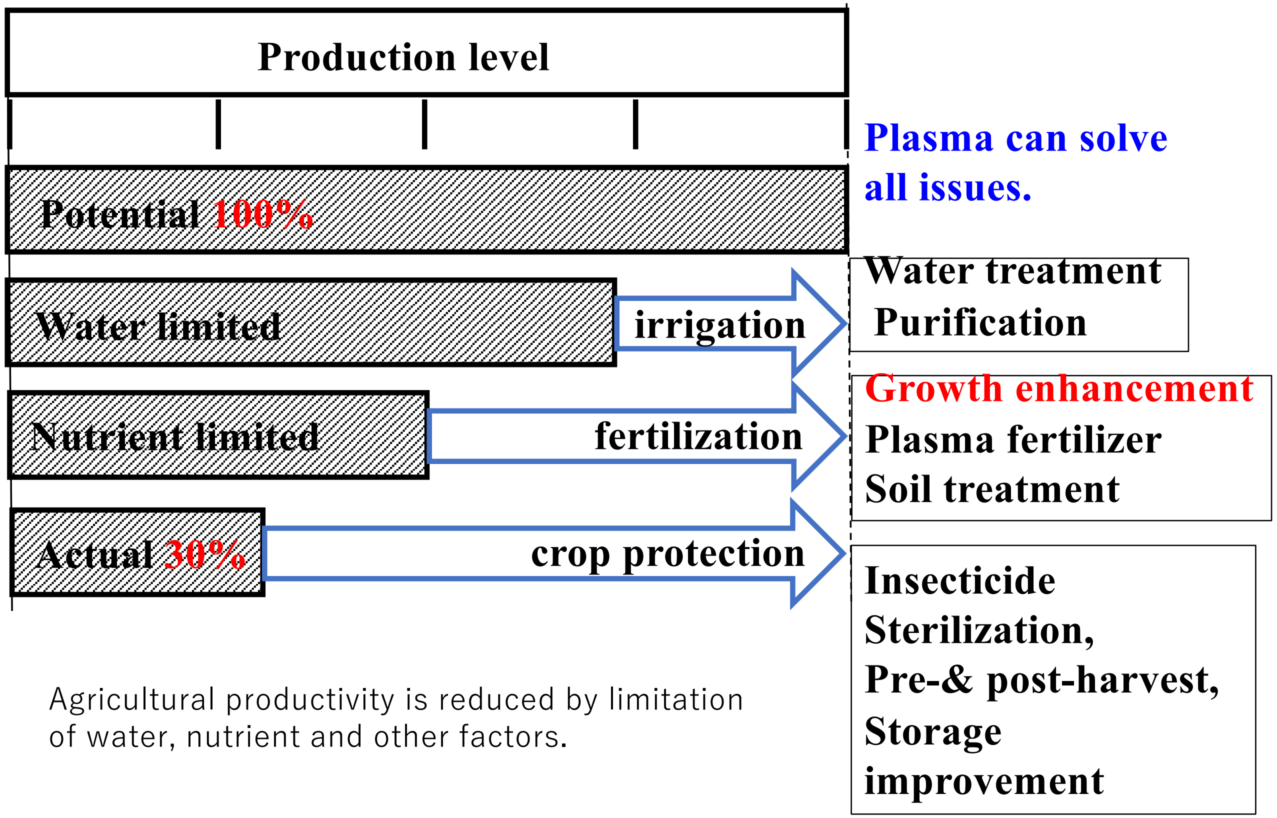
weight for control: 1.2 ± 0.2 (kg)
weight for plasma: 1.4 ± 0.3 (kg)
17 % up

BRIX for control: 23.7 ± 1.4 (%)
BRIX for plasma: 22.1 ± 1.5 (%)
7 % down

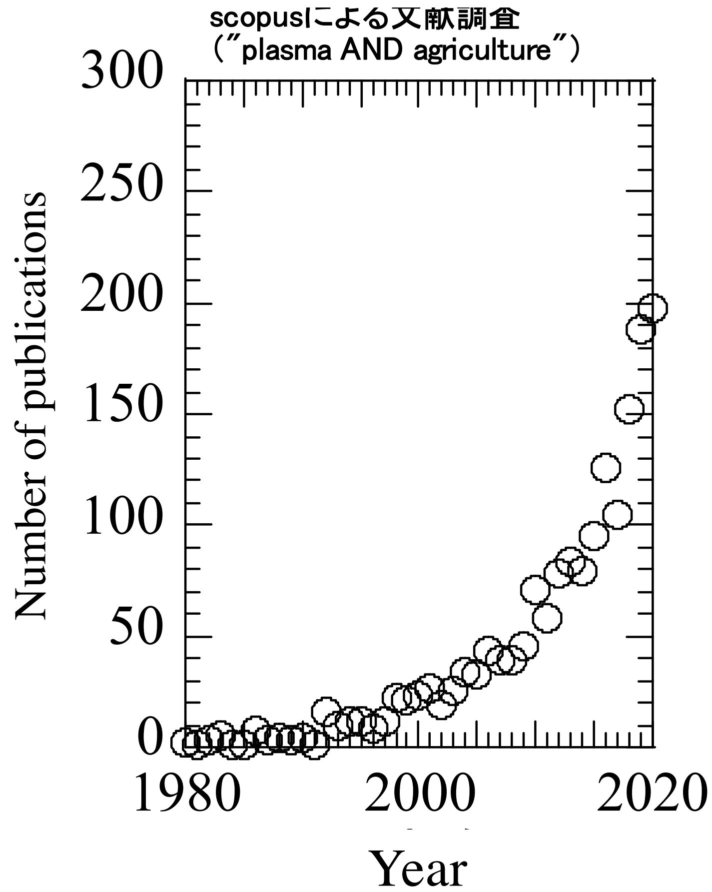
*BRIX: sugar content in juice

Increasing the use of water and chemical fertilizers has a negative impact on the environment and ecosystems. Plasma agriculture has the potential to increase production by controlling plant diseases and promoting sprouting and growth of crops while minimizing the impact on the ecosystem.

Approaches to improve agricultural productivity



Agricultural productivity is reduced by limitation of water, nutrient and other factors.



I. Adamovich, et al., 2022 J. Phys. D 55, 373001 (2022). Roadmap

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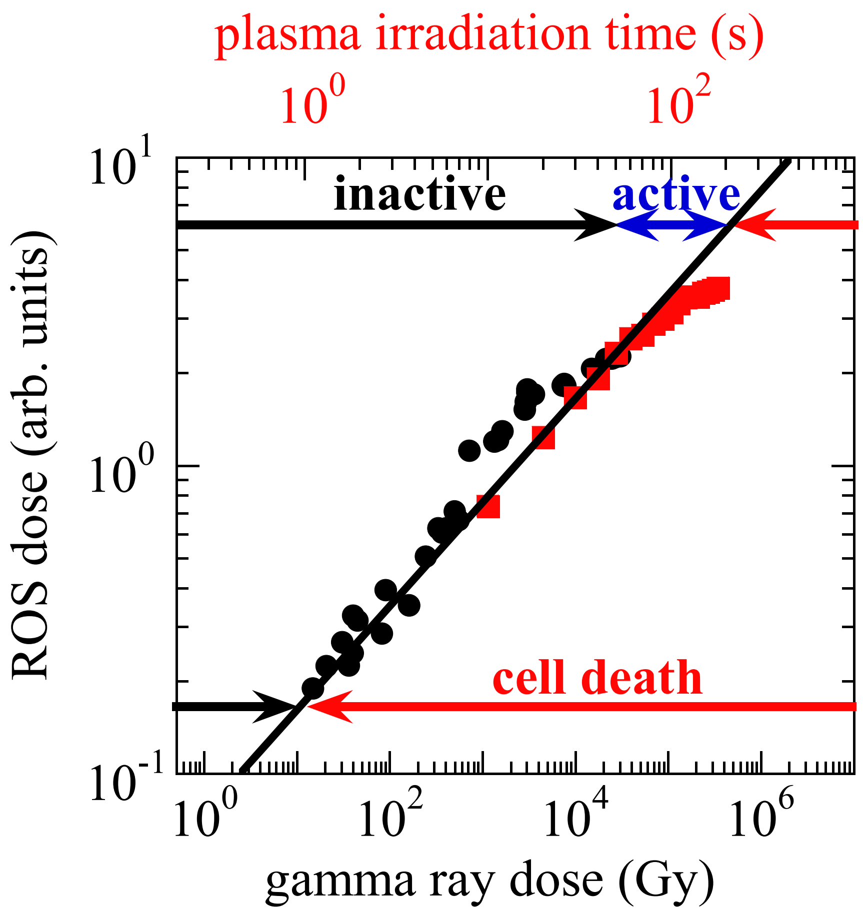
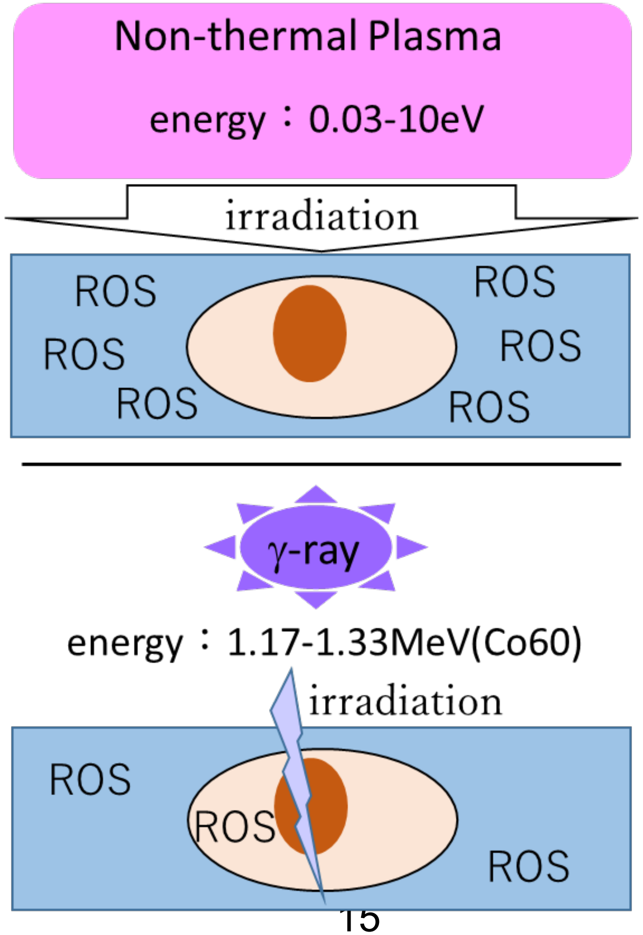
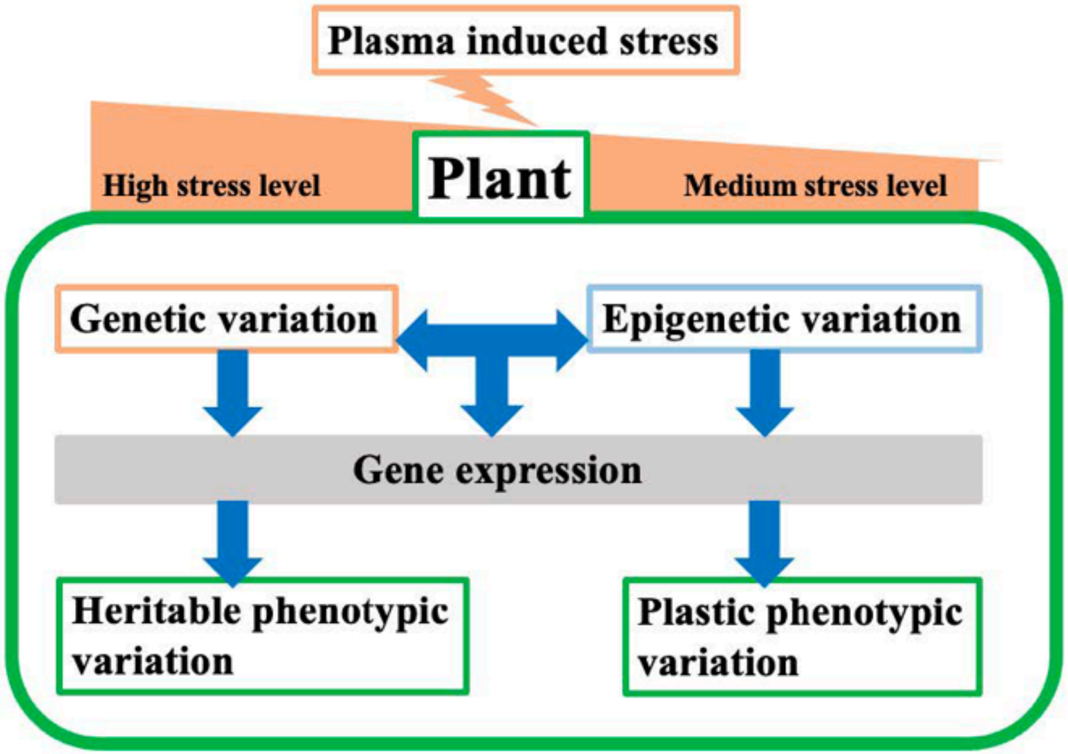
Advantage: Plasma supplies a high flux of ROS with low damage

1. **Plasma ROS safe dose is >1000 times higher than gamma rays.**
2. **Plasma supplies ROS outside cells, whereas gamma ROS outside and inside cells.**
3. **Plasma can provide activation to seeds, whereas gamma provides inactivation.**





How Plasma can be useful for agriculture?



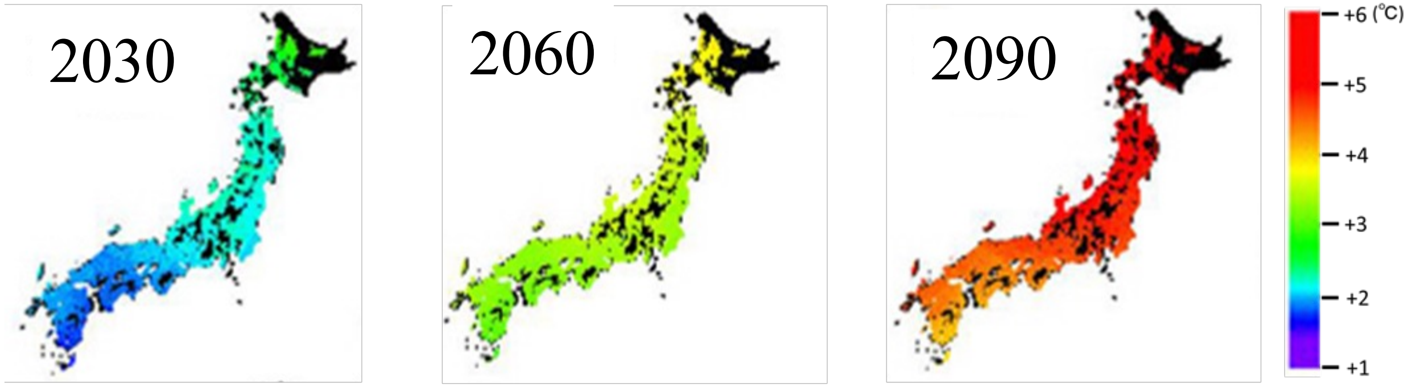
Potential interaction between genetic and epigenetic variation in plants under plasma induced stress.

5 years old Plumeria from seed (left) without and (right) with plasma irradiation

I. Adamovich, et al., J. Phys. D 55 (2022), 373001.

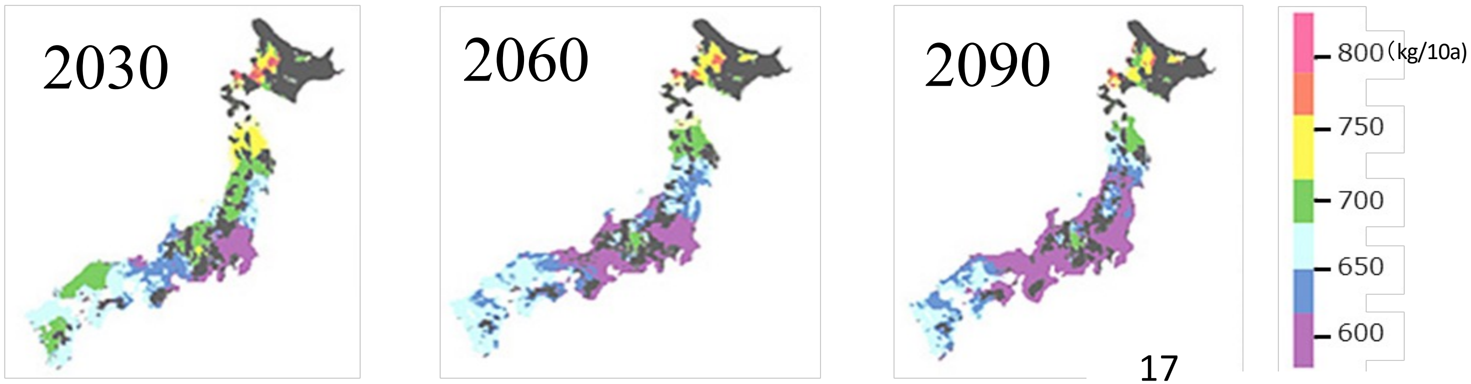
High temperature during growth of rice plants reduces the yield.

Average temperature from May to September in Japan increases year after year.



(http://mmsc.ruralnet.or.jp/)

Reduction in rice yield in Japan



Hayashi et al. (2001)

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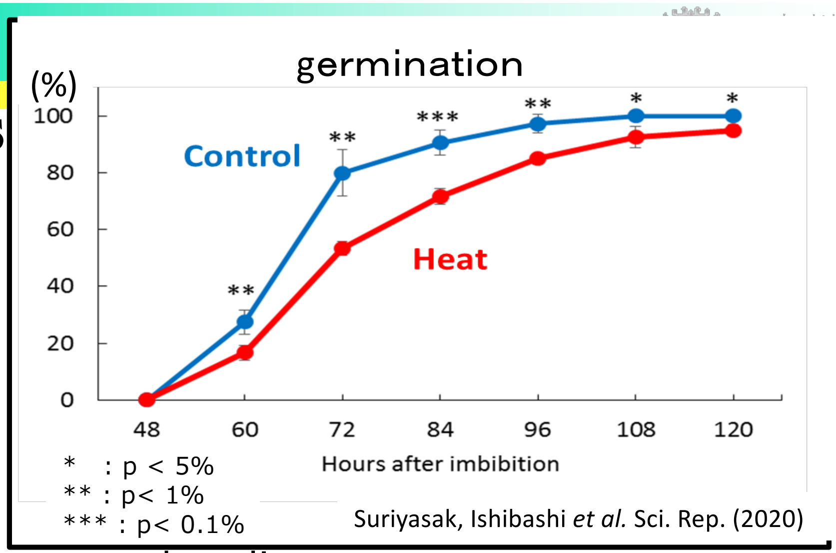
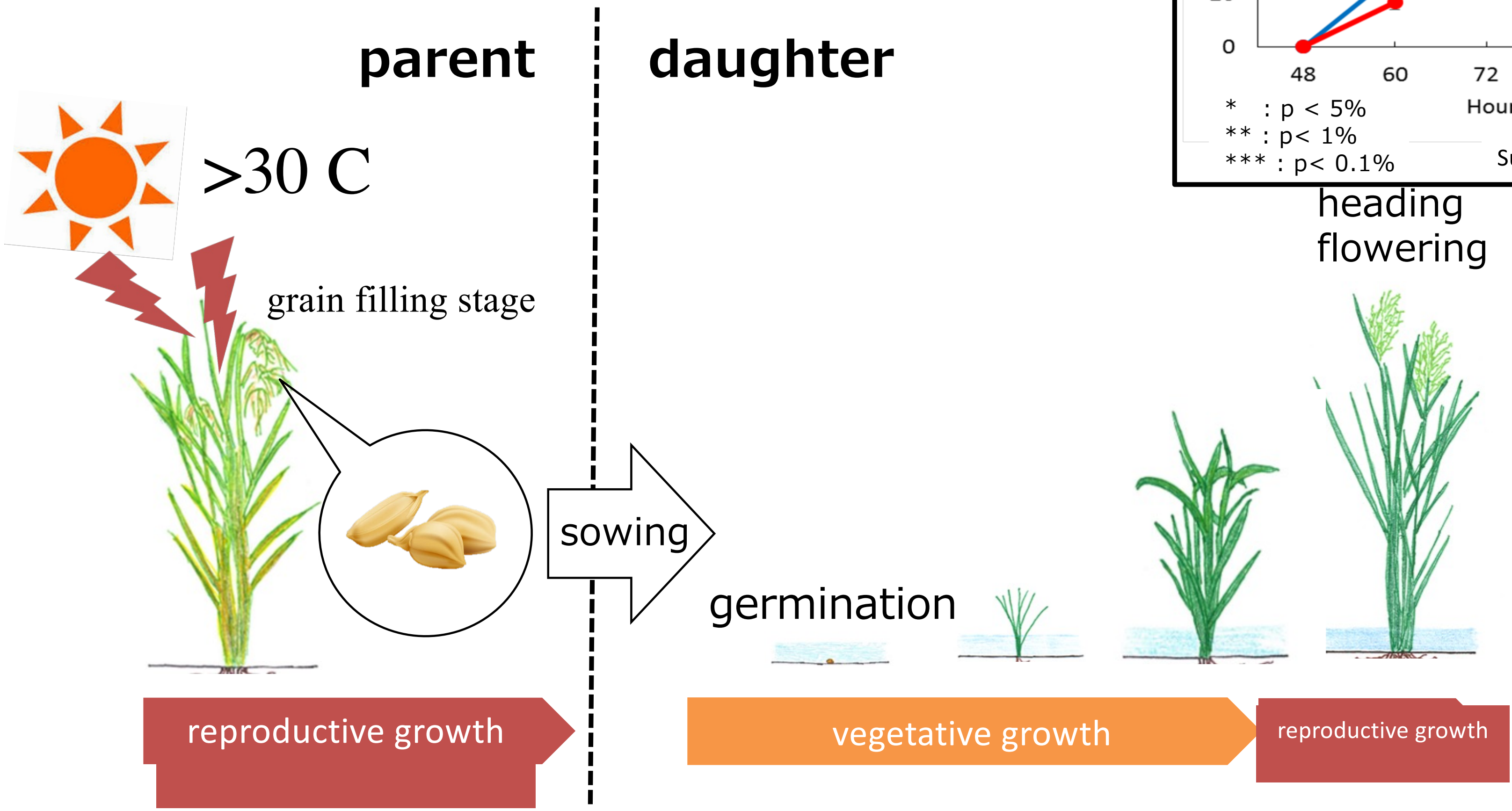
Delayed seed germination due to heat stress during grain filling stage of parent rice plants





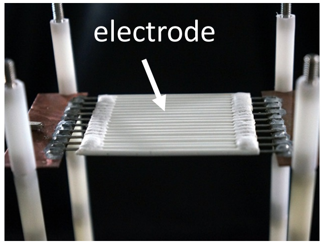
Materials and methods

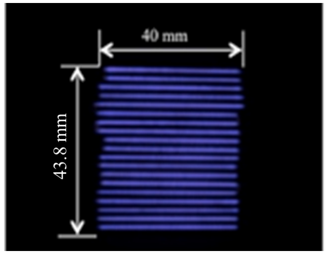
Material ; rice (Oryza sativa L.) :

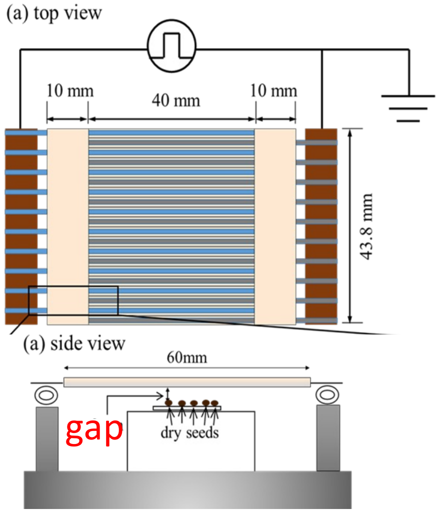
Control: unstressed seeds
Heat: seeds developed under heat stress
Heat+Plasma: plasma-irradiated seeds developed under heat stress

Atmospheric pressure DBD plasma
Treatment period: 180 s
Discharge voltage: 7.0 kV, 10kHz
Discharge power desity: 3.05 W/cm^2
Te=3-6eV, Ne=10^{13}-10^{14} cm^{-3}

Scalable dielectric barrier discharge plasma

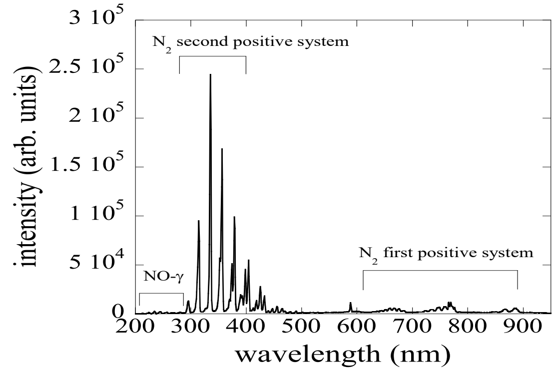






Photons, ions, radicals as well as thermal **flux** depend on irradiation **position**.
Dose is controlled by irradiation **duration**.

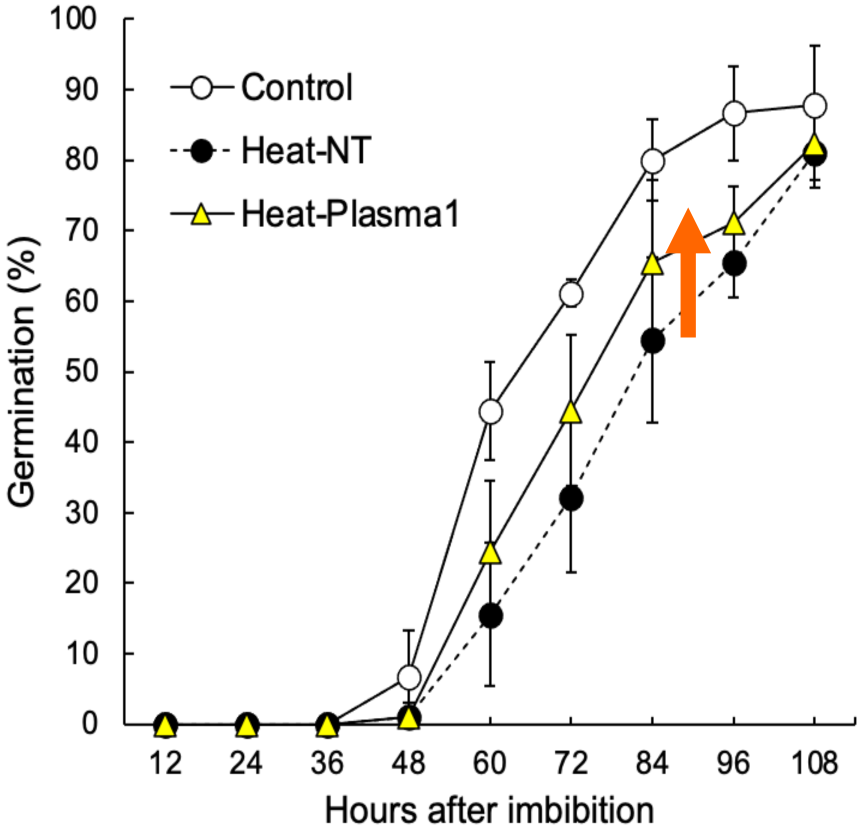
N_2 2nd positive band (280-400 nm) and NO-γ (200-260 nm) are observed in air DBD discharges.



S. Kitazaki, et al., Curr. Appl. Phys. 14 (2014) 149.

Germination test: Rice

Plasma irradiation to rice seeds with heat stress improves germination characteristics.



C. Suriyasak, et al., ACS Agric. Sci. Technol. 1, 5 (2021).

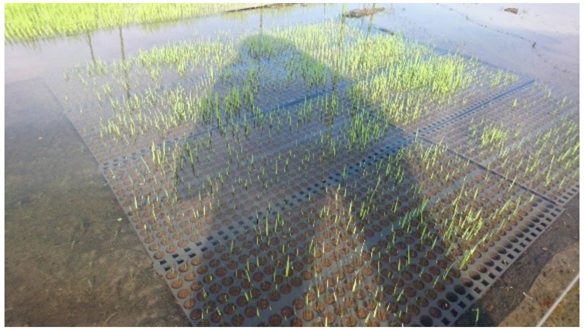
Field test @ Fukuoka, Japan (Rice: HINOHIKARI)

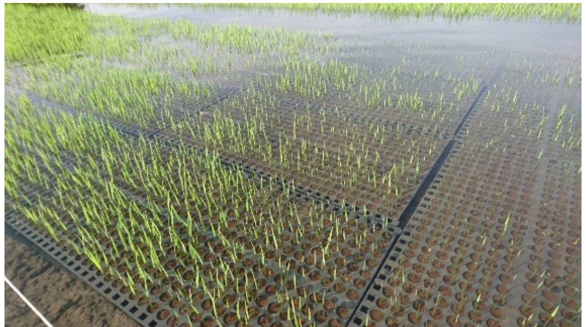
Day 6 after sowing

Day 14: plasma treated plants grow faster.

control

plasma





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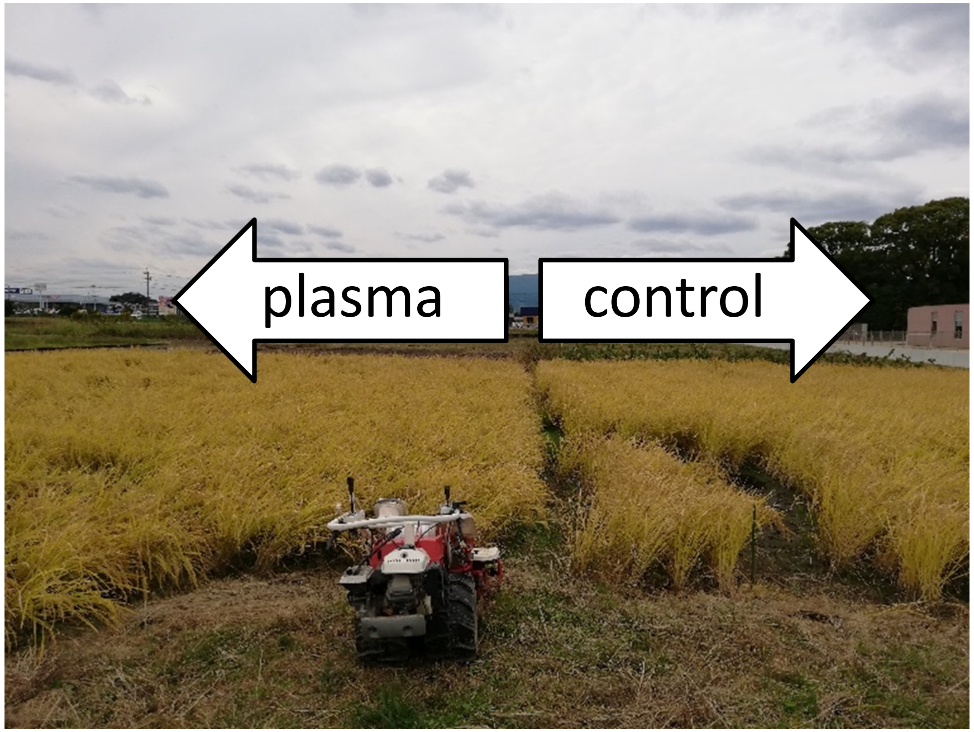
Field test@ real farm, Harvest on 31st, October, 2018 to 2023

Without agricultural chemicals, pesticide, herbicide.

Fresh weight for 7 rootstocks:
Plasma: 1.65 kg, 113% @2018
Control: 1.46 kg, 100% @2018



<Weight of unhulled rice in 2018>
Plasma:189.29kg, 104% @2018
Control: 181.98kg, 100% @2018

Number of samples:
5814 samples (rootstocks)
for each condition.

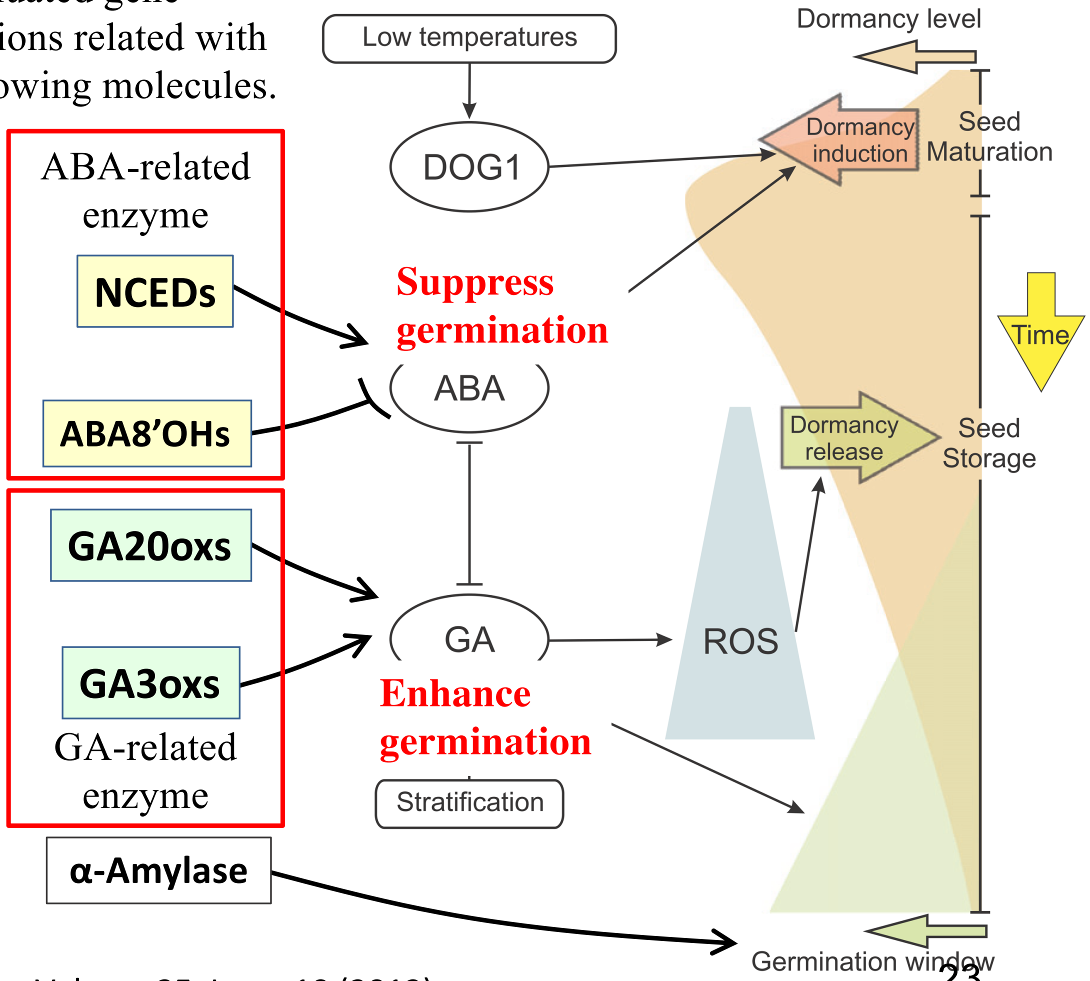
<Subacute toxicity test>
-6 mice for each conditions
-There is no difference among the administration conditions.

< **Now**: rice in fully organic cultivation>
30% increase production
3,000 Yen input of plasma agri. leads to 30,000 Yen output increase.

Germination mechanism and related molecules

ABA and GA are plant hormones which control germination.

We evaluated gene expressions related with the following molecules.



K. Graeber et al. Plant, Cell & Environment Volume 35, Issue 10 (2012)

Typical gene expression

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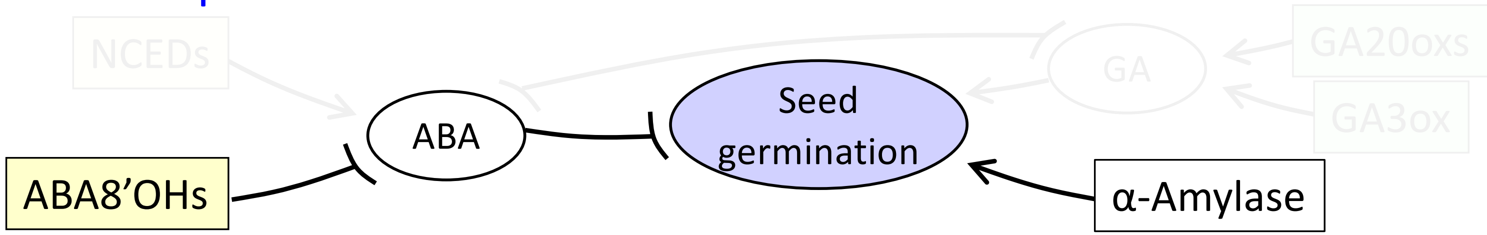
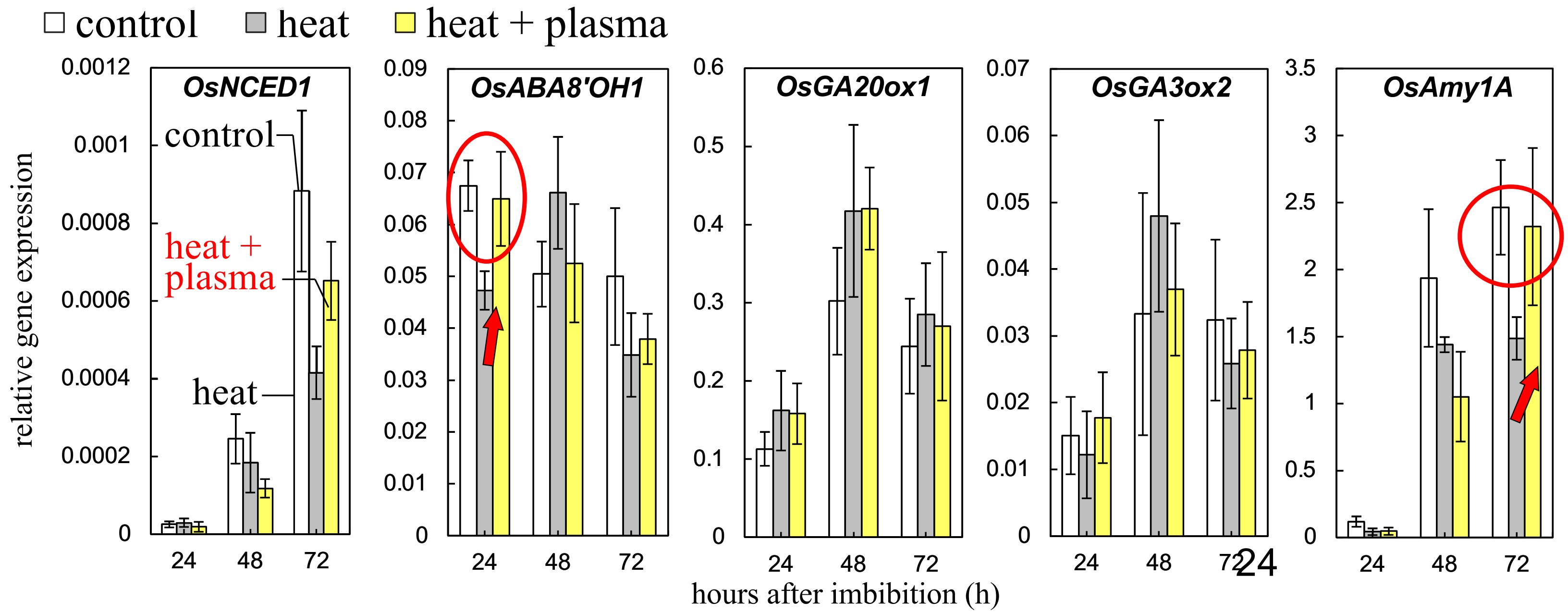
Kyushu University

- Gene expression of OsABA’8OHs and OsAmy1s is increased by plasma irradiation to seeds with heat stress.
- OsNCEDs, OsGA20oxs and OsGA3oxs are not changed by plasma.

Effects of plasma irradiation

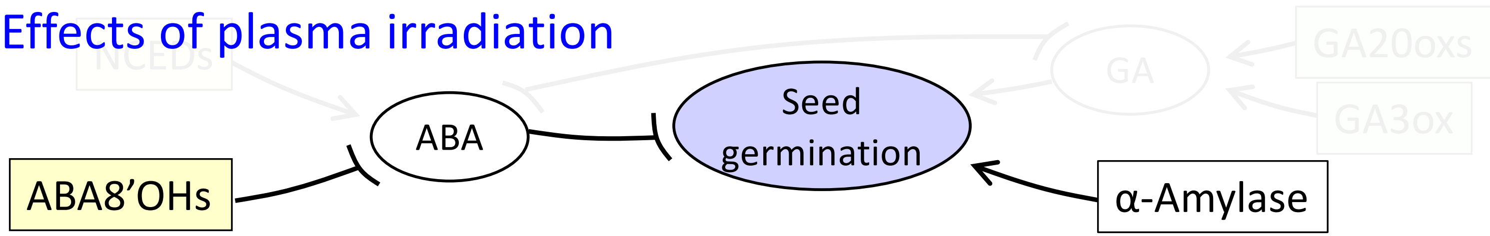




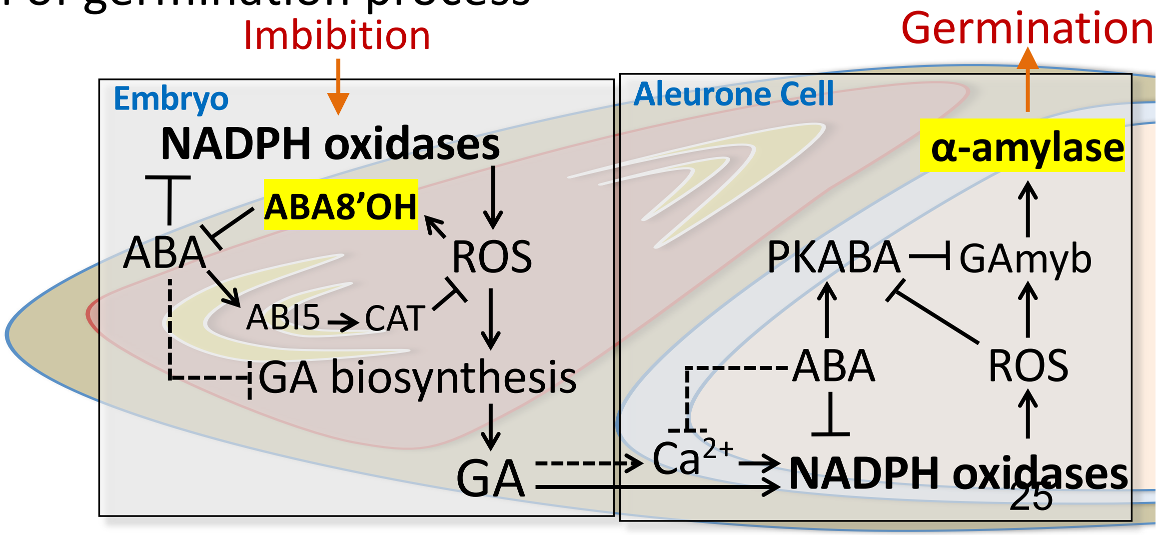
Discussion

- Plasma irradiation has less effective on gene expression of GA bio-synthesis.
- Plasma-enhanced germination might be different from standard physiological germination process ⇨ **epigenetic change?**

Effects of plasma irradiation



Metabolism of germination process



MeDIP-qPCR: Methylation level test

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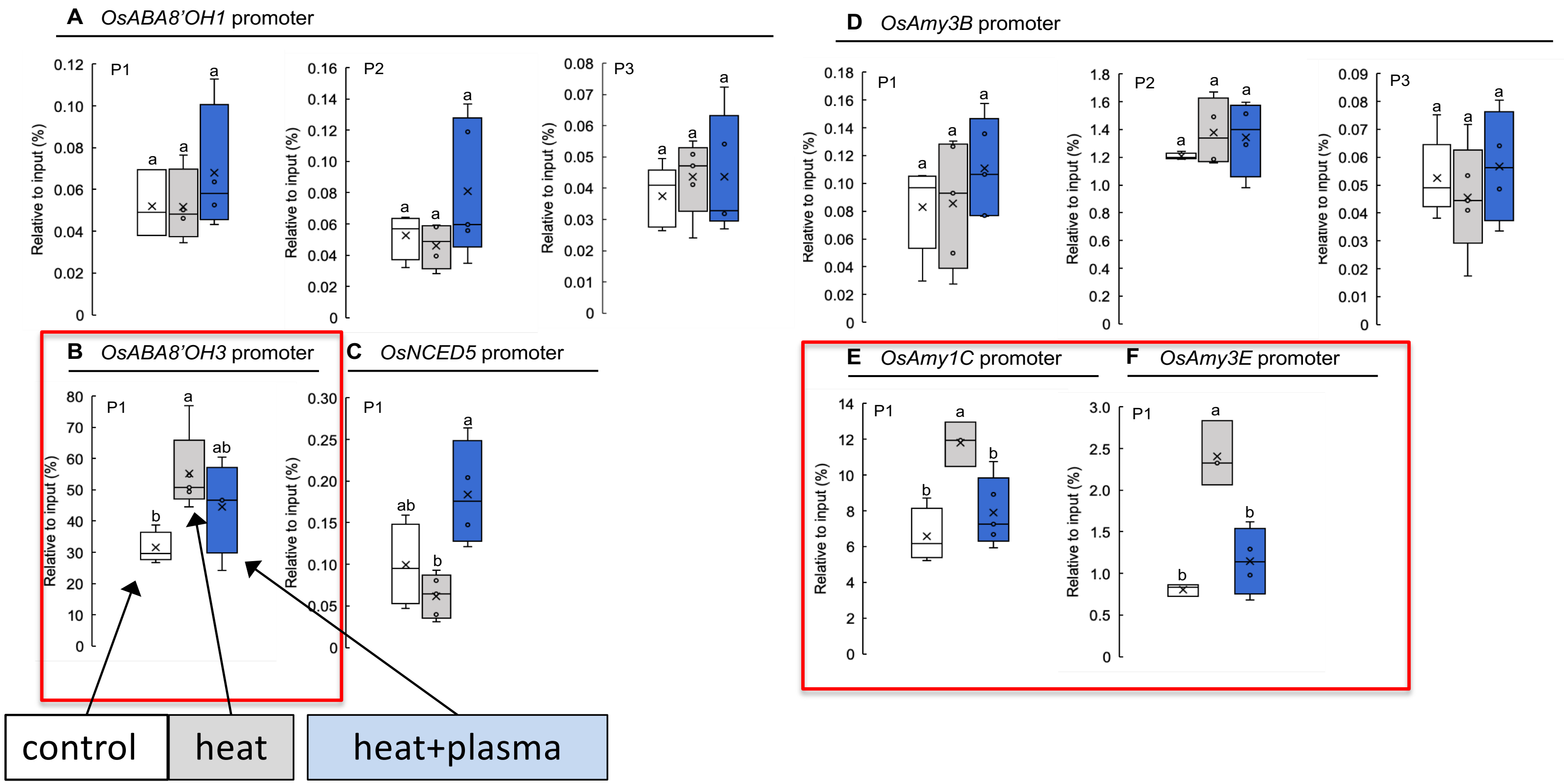
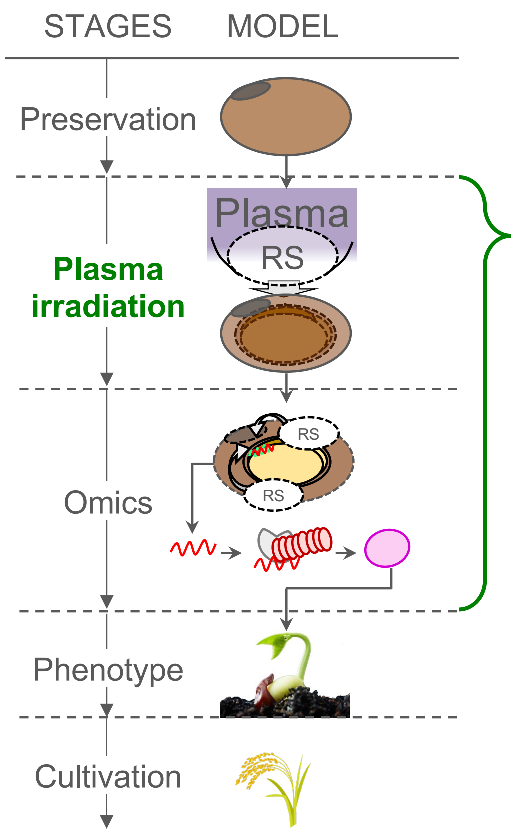
Plasma treatment decreases the DNA methylation levels in seeds related to germination.

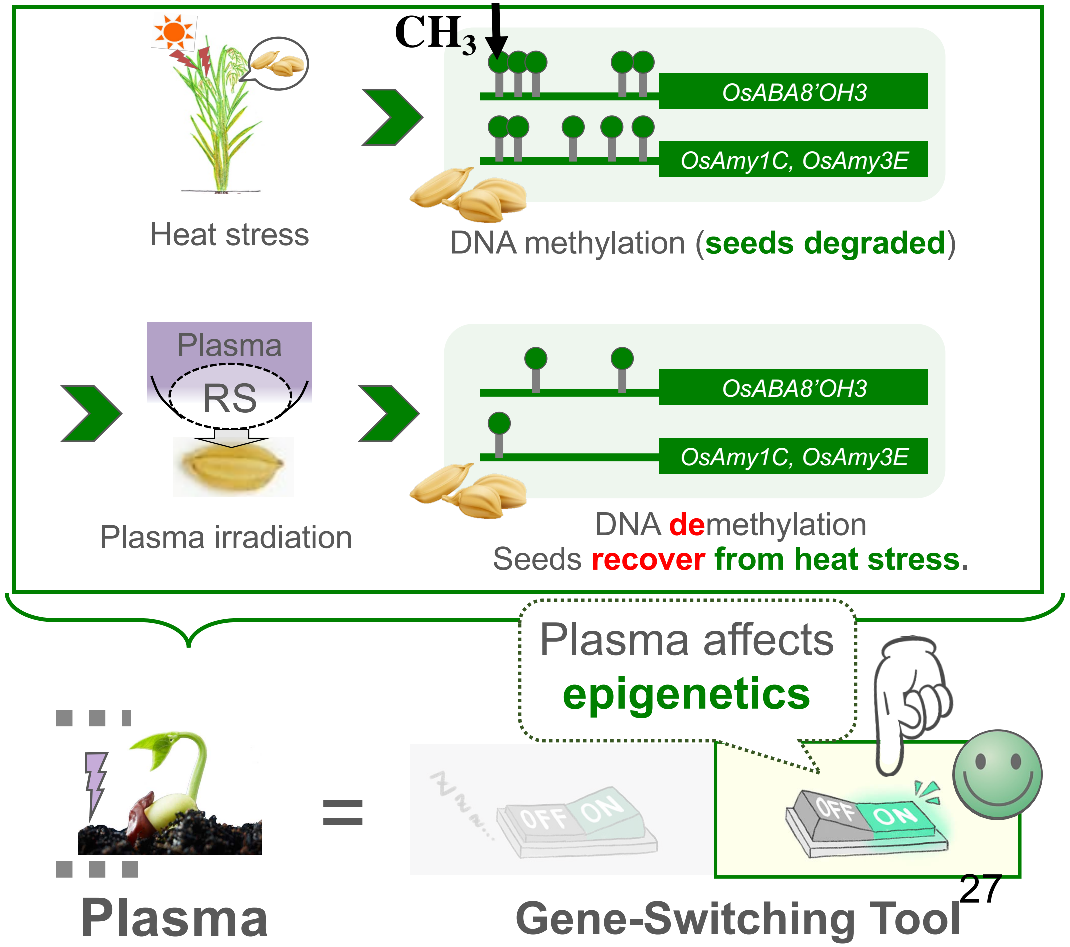
OsABA8'OH3, OsAmy1C and OsAmy1E promoters



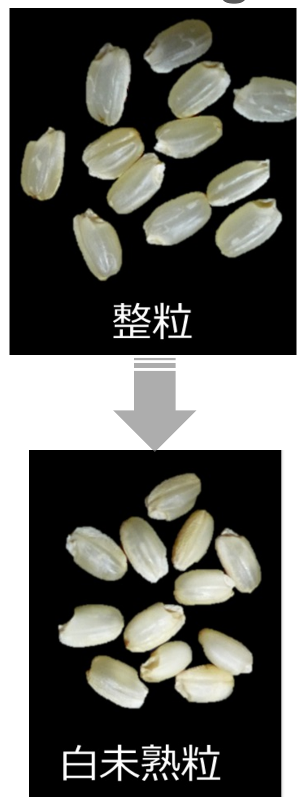
Our new finding of "Plasma Agriculture"

Plasma irradiation to heat stressed seeds leads to DNA demethylation (= hypo-methylation).

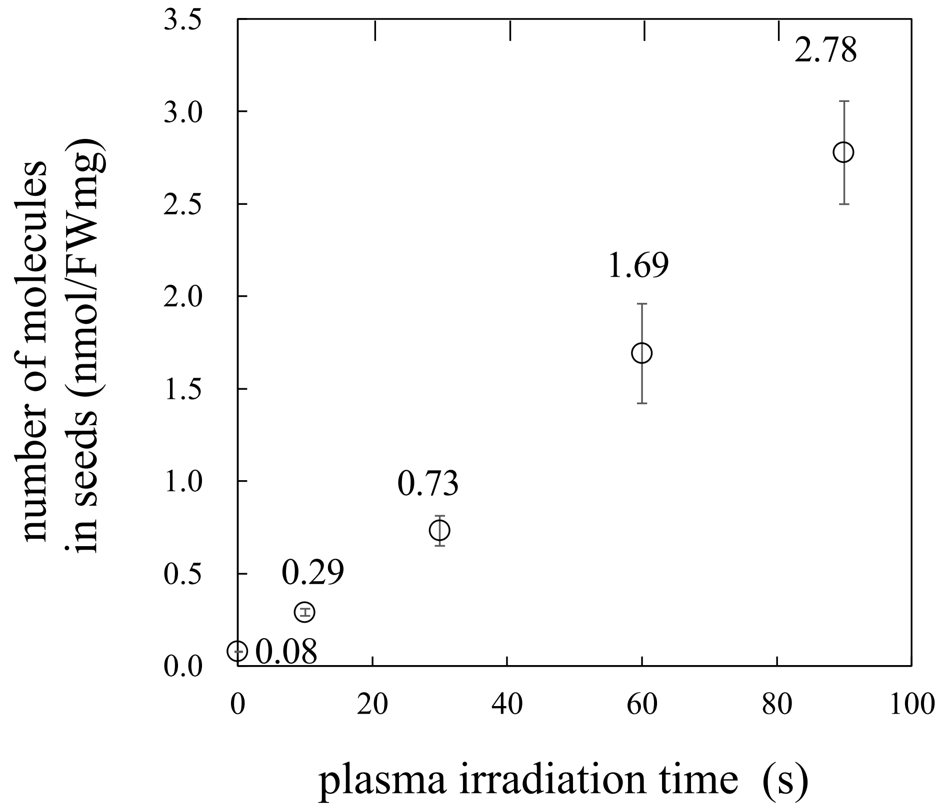




Heat stress by warming



Detection of NO_3^- introduced into seeds from plasma using LC-MS/MS



FWmg: Fresh weight mg

0.08 nmol/FWmg without plasma

20 times increase

1.69 nmol/FWmg with 1 min plasma

1 min. plasma irradiation realizes 20 times higher NO_3^- concentration in seeds than that without plasma irradiation.

Word 1st results of direct quantitative measurements of RONS concentration in seeds introduced by plasma irradiation.

T. Okumura, et al., Scientific Reports 12 (2022) 1-11.

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Future Vision: To establish plasma agriculture

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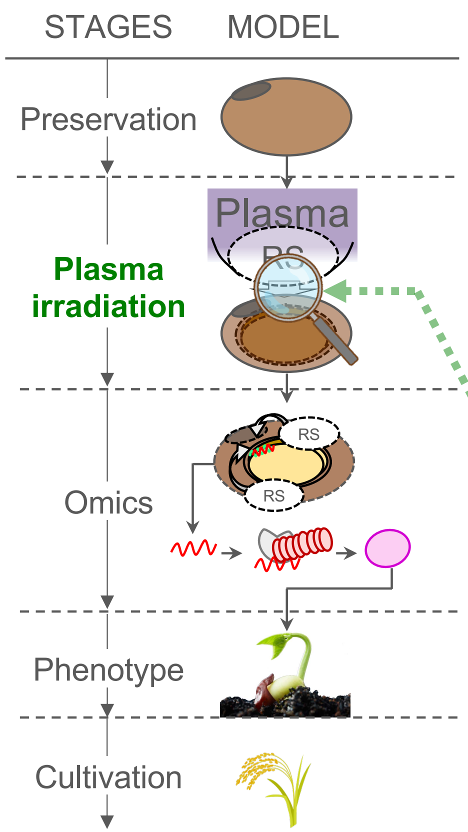
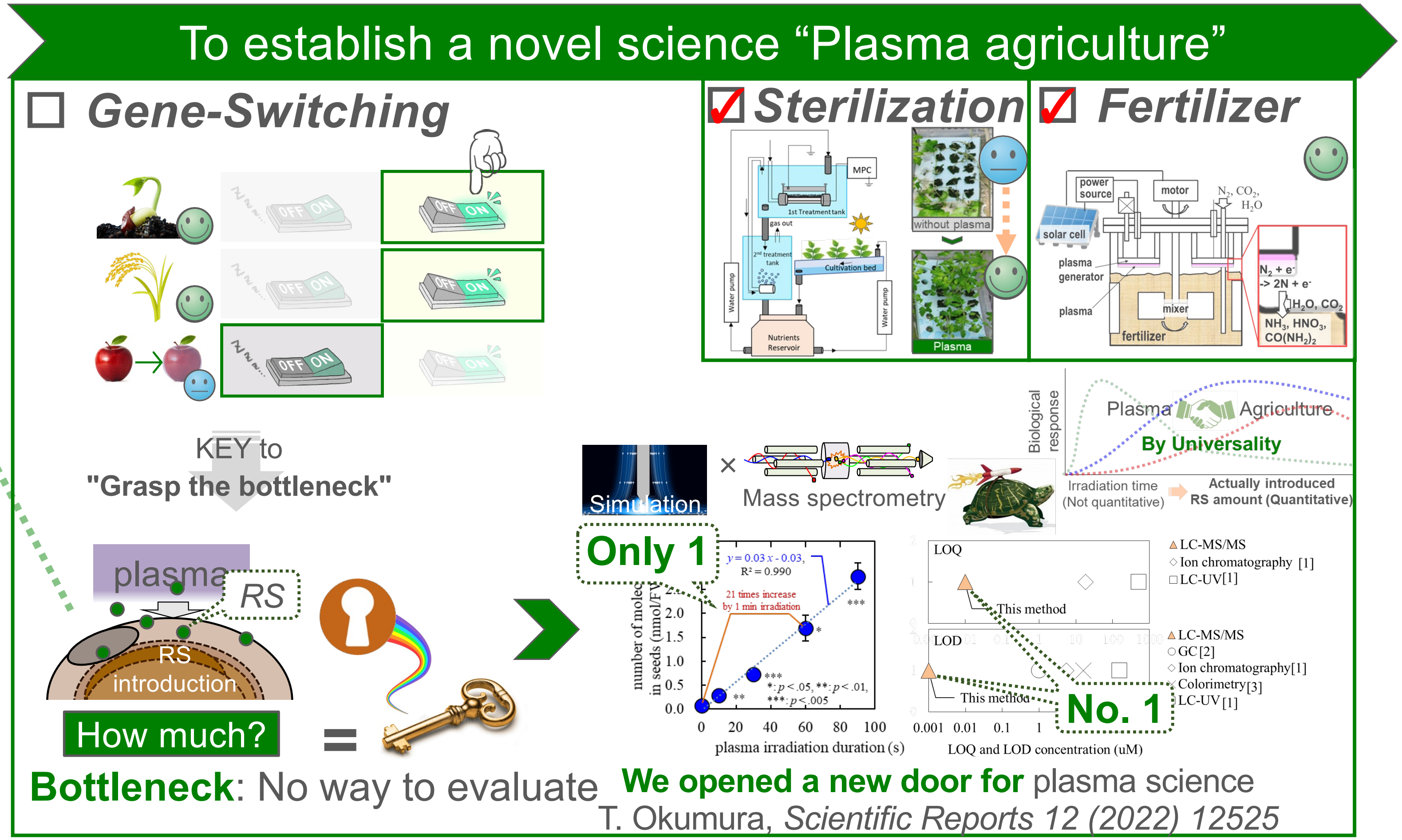
■ Bottleneck and our scientific **breakthrough**





Missing-link

Breakthrough!

Summary

history (season)
cultivation conditions

Plasma (minutes)
RONS、 ions, photons

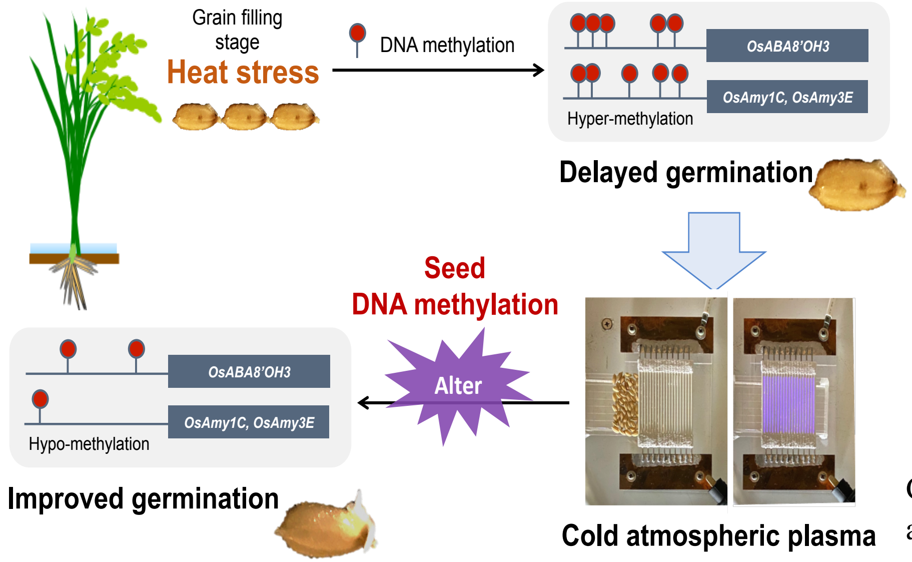
seed

Heat stress induces hyper-methylation leading to delayed germination.

Plasma irradiation induces hypo-methylation improving germination

phenotype

germination/ growth etc.



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Alterations of DNA Methylation Caused by Cold Plasma Treatment Restore Delayed Germination of Heat-Stressed Rice (*Oryza sativa* L.) Seeds

Chetphilin Suriyasak, Kota Hatanaka, Hayate Tanaka, Takamasa Okumura, Daisuke Yamashita, Pankaj Attri, Kazunori Koga, Masaharu Shiratani, Norimitsu Hamaoka, and Yushi Ishibashi*

Cite This: https://dx.doi.org/10.1021/acsagscitech.0c00070 Read Online

C. Suriyasak et al., ACS Agricultural Science and Technology 1 (2021).

Summary #1

Scientific Impact

1. Low-temperature plasma irradiation can correct DNA methylation
2. Possibility of controlling gene expression by low-temperature plasma irradiation
3. Contribution to elucidation of gene functions?

Social impact

Contribution to solving problems in rice and wheat cultivation associated with global warming

Summary #2

Low-Temperature Plasma Provides a New Means of Improving Agricultural Productivity

Low-temperature plasma delivers high concentrations of active chemical species to living organisms without damage
Appropriate low-temperature plasma irradiation is beneficial to agriculture
No adverse effects on safety, taste, color, etc.

Remaining issues: Significant contribution to solving the food crisis
1. Elucidation of the mechanism through interdisciplinary research
2. Application to actual agriculture
3. Application to various plant species

Seven Pros of Plasma Agriculture:

1. Increased crop yields: Plasma agriculture has the potential to enhance plant growth and increase crop yields. Plasma treatments can stimulate seed germination, improve nutrient absorption, and enhance photosynthesis, leading to healthier and more productive plants.
2. Pest and disease control: Plasma can be effective in eliminating pests, pathogens, and weeds. Plasma treatments can help reduce the reliance on chemical pesticides and herbicides, potentially resulting in reduced environmental contamination and lower health risks for farmers and consumers.
3. Water and soil improvement: Plasma treatments have the potential to improve water and soil quality. Plasma can remove contaminants and toxins from water, making it safer for irrigation. It can also break down organic matter and improve nutrient availability in the soil.
4. Reduced chemical inputs: Plasma agriculture has the potential to reduce the need for synthetic fertilizers and pesticides. This can lead to lower costs for farmers and reduced environmental impact, including less pollution of water bodies and reduced soil degradation.
5. Extended shelf life: Plasma treatments can help extend the shelf life of fruits and vegetables. By reducing the growth of spoilage-causing microorganisms, plasma can help preserve the freshness and quality of produce, reducing food waste.
6. Cost and infrastructure: Implementing plasma agriculture can be inexpensive,. The rental or co-ownership of the plasma equipments may be cost-effective for many farmers even in developing regions.
7. Energy consumption: Plasma generation requires energy, and the energy consumption associated with plasma agriculture is evaluated below 3% of the energy of whole agricultural processes. The use of electricity from on-site renewable energy sources may contribute to sustain plasma.

Three Cons of Plasma Agriculture:

1. Lack of long-term studies: Plasma agriculture is still a relatively new field, and there is limited long-term research on its effects. More studies are needed to fully understand the potential environmental and health impacts associated with plasma treatments.
2. Potential unintended consequences: While plasma treatments can target pests and pathogens, there is a risk of unintended effects on beneficial organisms. It is crucial to study and minimize any potential harm to beneficial insects, pollinators, and other organisms in the ecosystem.
3. Regulatory challenges: The adoption of plasma agriculture may face regulatory hurdles, as the technology is still emerging and may not fit within existing regulatory frameworks. This could slow down its widespread implementation and commercialization.

It's important to note that plasma agriculture is an evolving field, and further research and development are necessary to fully understand its potential benefits and drawbacks.