Institution: Royal Holloway, University of London

Unit of Assessment: 5 Biological Sciences

Title of case study: Improving crop seed quality through environmentally sustainable technologies to benefit the seed industry and promote food security

Period when the underpinning research was undertaken: 2012-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor Gerhard Leubner	Chair of Plant Biochemistry	2012-date
Dr Tina Steinbrecher	Research Fellow in Biomechanics	2012-date

Period when the claimed impact occurred: 2016-2020

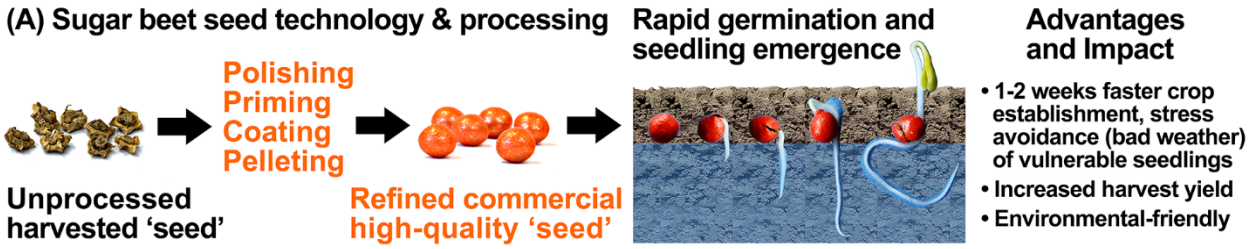
Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

High-quality seed is essential for enhanced seedling performance under stress (climate change) and consequently for yield and food security. Research by RHUL's Seed Group has led to environmental-friendly technologies that refine quality, storability and resilience of crop seeds (2019 global seed market USD61,500,000,000). This has commercially benefitted the world's leading sugar beet seed supplier (KWS SAAT SE) by enabling it to improve production, quality control processes, and sustainable technology. In the UK, the research has facilitated the 'Rocket Science Project' for food security and climate change awareness, and helped a leading independent vegetable seed and breeding company (Tozer Seeds) to advance quality management and driving employment opportunities and an investment of GBP500,000 in a new R&D facility.

2. Underpinning research

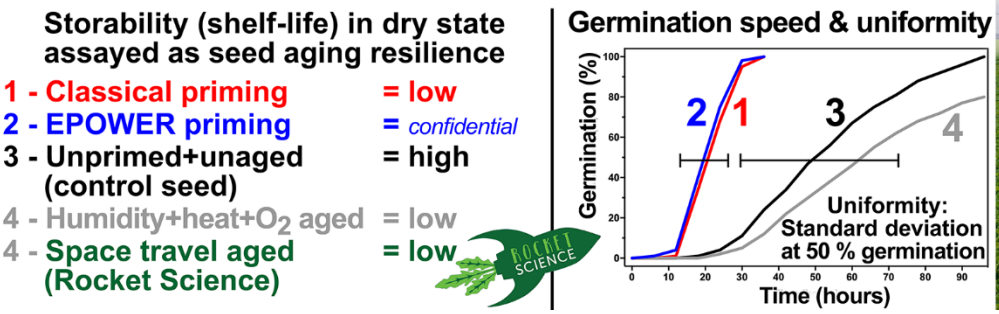
Molecular and technological innovation led by Royal Holloway resulted in high-quality commercial seed that delivers enhanced germination performance (vigour) and faster crop establishment (Fig. A). Seed technologies break seed dormancy, enhance germination under environmental stress and protect the vulnerable seedling stages against extreme weather events, including non-optimal temperatures (heat or chilling), flooding and drought (climate change). This research refined crop seed processing technologies including polishing, priming, coating and pelleting, and delivered refined high-quality commercial seed (Fig. B) [**R1**]. This is vital for food supply chain resilience to ensure global food security given the unknown effects of future climate change on crop production.



Leubner and Steinbrecher led interdisciplinary collaborative research with the seed industry (including Tozer Seeds and KWS) on the mechanisms of seed responses to environmental stresses [**R2**], by integrating molecular seed biology, agri-technologies and biomechanics [**R3**]. Their Seed Science Research Group published in international recognized peer-reviewed journals, such as *PNAS*, *Nature Communications* and *New Phytologist* and wrote highly cited reviews. This research (publications including [**R1 to R6**]) has addressed local and global challenges: Beyond primary crop production [**R1 to R3**], seed quality is important for milling [**R4**], food processing and for ageing resilience during dry post-harvest seed storage ("shelf-life", Fig. B). Seed quality loss during storage is a major problem for company warehouses [**R5**],

seed banks, and extra-terrestrial food security during spaceflight [**R6**]. While seed priming enhances germination vigour, it often compromises seed storability. To mitigate this, RHUL developed and patented EPOWER priming as an innovative, environmental-friendly seed technology (Fig. B).

(B) Crop seed storability (shelf-life, aging resilience) and seed performance



Examples of RCUK/UKRI and industry-funded seed quality and technology research:

- Projects led by Leubner with KWS SAAT SE (direct funding between 2013 and 2022) into "sugar beet seed quality and stress resilience" have revealed mechanisms underpinning seed and seedling growth responses to abiotic stresses (heat, chilling, salinity, drought, flooding). This has contributed to our knowledge on seed temperature sensing [**R2**], dormancy mechanisms [**R3**], and has delivered molecular markers for seed processing, priming (Fig. A) and storage (Fig. B).
- Projects led by Steinbrecher with KWS SAAT SE (direct funding between 2014 and 2019) into "sugar beet pericarp and pellet biomechanics" and Buehler into "cereal grains" (direct funding between 2012 and 2014) have delivered biomechanical techniques and assays supporting seed processing technology [**R1**] and grain milling [**R4**]. Together with BBSRC-funded research (BB/M000583/1), this revealed the importance of biomaterial properties in seeds and seed technology [**R1 to R4**].
- Projects led by Leubner and Steinbrecher with the company Tozer Seeds (Agri-Tech/ISCF funding between 2016 and 2019) have delivered novel molecular marker and diagnostic assays for vegetable and salad seed ageing and storage resilience (warehouse "shelf-life", Fig. B) [**R5**]. Their re-search in the Rocket Science Project has revealed seed ageing markers during spaceflight [**R6**].
- Projects led by Leubner and Steinbrecher with the company Elsoms Seeds and electrical engineers at Loughborough University (BBSRC and Agri-Tech/Innovate UK funding between 2014 and 2021) into "vegetable seed quality" have led to the development of EPOWER, a novel environmental-friendly seed priming technology. EPOWER priming utilises gas plasma technology, which induces protection mechanisms to provide refined high-quality seed with better storability than classical priming (Fig. B). RHUL patented EPOWER in 2019 (application number 1916576.0).

Funding/Awards:

Total funding of RHUL's Seed Group during the REF period (2014 to 2020): GBP4,600,000. This includes directly linked to this impact case a mix of direct industry funding from KWS SAAT SE, the world-leading supplier of sugar beet seeds (>GBP1,000,000, 2013-2020); two Agri-Tech/ISCF-funded research projects with Tozer Seeds and Elsoms Seeds in the UK (GBP194,540: 2018 to 2019, GBP189,595: 2014 to 2016); 2 BBSRC-funded projects (GBP688,343: 2015 to 2018; GBP149,715: 2019 to 2021); and 2 BBSRC iCASE Studentships (each >GBP100,000: 2016 to 2020, 2015 to 2021); and consultancy to the KWS Sugar Beet Quality Group by Prof Leubner (2013 to 2021) and Dr Steinbrecher (2020 to 2021).

3. References to the research

Names in **Bold** are **staff** (including former staff) of **Royal Holloway University of London**. QI: All references are **OpenAccess** publications in internationally recognized peer-reviewed journals.

[**R1**] **Ignatz M***, **Hourston JE***, Tureckova V, Strnad M, Meinhard J, Fischer U, **Steinbrecher T***, **Leubner-Metzger G*** (2019) The biochemistry underpinning industrial seed technology

and mechanical processing of sugar beet. ***Planta*** 250:1717-1729; https://doi.org/10.1007/s00425-019-03257-5 (*marks shared first/corresponding/last author)

[**R2**] **Graeber K**, Linkies A, **Steinbrecher T**, Mummenhoff K, Tarkowská D, Turečková V, **Ignatz M**, Sperber K, **Voegele A**, de Jong H, Urbanová T, Strnad T, **Leubner-Metzger G** (2014). DELAY OF GERMINATION 1 mediates a conserved coat-dormancy mechanism for the temperature- and gibberellin-dependent control of seed germination. ***Proceedings of the National Academy of Sciences USA*** 111:E3571-E3580, https://doi.org/10.1073/pnas.1403851111

[**R3**] Sperber K*, **Steinbrecher T***, **Graeber K**, Scherer G, Clausing S, Wiegand N, **Hourston JE**, Kurre R, **Leubner-Metzger G***, Mummenhoff K* (2017). Fruit fracture biomechanics and the release of *Lepidium didymum* pericarp-imposed mechanical dormancy by fungi. ***Nature Communications*** 8:1868, https://doi.org/10.1038/s41467-017-02051-9

[**R4**] **Hourston JE**, **Ignatz M**, **Reith M**, **Leubner-Metzger G**, **Steinbrecher T** (2017). Biomechanical properties of wheat grains: the implications on milling. ***Journal of the Royal Society Interface*** 14:20160828, https://doi.org/10.1098/rsif.2016.0828

[**R5**] **Hourston JE**, **Pérez M**, Gawthrop F, Richards M, **Steinbrecher T**, **Leubner-Metzger G** (2020). The effects of high oxygen partial pressure on vegetable *Allium* seeds with a short shelf-life. ***Planta*** 251:105, https://doi.org/10.1007/s00425-020-03398-y

[**R6**] **Chandler J**, Haas F, **Khan S**, **Ignatz M**, Gawthrop F, Griffiths A, Rensing S, **Leubner-Metzger G** (2020). Rocket Science: The effect of spaceflight on germination physiology, ageing, and transcriptome of *Eruca sativa* seeds. ***Life*** 10:49, https://doi.org/10.3390/life10040049 (Special Issue “Frontiers of Astrobiology”)

4. Details of the impact

The global seed market is valued at USD61,500,000,000 in 2019 and expected to grow at CAGR of 7.6% to USD86,000,000,000 by 2026. Under changing future climate scenarios, the seed sector and food production chains will be affected, undermining food security. Research led by Leubner and Steinbrecher revealed that there is an urgent need to better understand the resilience of seeds in the light of intensifying climate change and environmental stressors. Working with commercial companies and academic partners, the team at RHUL delivered impact in three areas: commercial revenue generation, investment and improvement in seed production processes; local employment generation; and public engagement and communication of science.

(1) Commercial impact: revenue generation, internal investment, improved production

Research led by Leubner and Steinbrecher in RHUL's Seed Group has commercially benefitted seed production companies by enhancing and refining the quality, storability and ageing resilience of their crop seeds with environmental-friendly technologies. The refined seed delivers higher value for seed companies and provides increased revenue from world-wide sales. The enhanced performance of high-quality seed improves crop establishment for farmers which increases harvest yield potential and resource efficiency, and therefore more widely food security and sustainability especially in times of the climate emergency.

Commercial benefit to KWS SAAT SE

The research and consultancy of Leubner and Steinbrecher has commercially benefitted KWS SAAT SE by **improving production and quality control processes** and thereby helping it to maintain its position as the world's leading sugar beet seed supplier. “*KWS retains ~60% share of the global sugar beet market and is leader in most of the individual markets*” [S1]. During the reporting period (2014 to 2020), seed net sales in their sugar beet segment increased by 31.4% to EUR461,000,000 (in 2018/19) and Earnings Before Interest and Taxes (EBIT) by 155.8%. "*As a seed specialist, in our corporate strategy, we strive to contribute to greater sustainability in agriculture*" (Dr Henning von der Ohe, Head of Corporate Development). KWS and RHUL's Seed Group have developed a long-standing working relationship with collaboration publications including [R1] and continuous project funding by KWS with a total of GBP1,043,000 during 08/2013 and 07/2020.

For Dr Uwe Fischer, KWS Manager Seed Research, it is clear that the company's collaboration with RHUL has contributed to its success: "*Our high-yielding varieties together with top-quality seed makes us the leader in the global sugar beet seed market… **RHUL Seed Group's multi-***

***disciplinary research and expert knowledge has contributed to our success in this market**. In particular, Leubner's research into the abiotic stress resilience of the vulnerable early phases of crop establishment with sustainable seed quality assays and pioneering molecular technology, and Steinbrecher's novel biomechanical assays for seed pellets have helped us to make improvements in different but essential parts of our operation. During the reporting period (2014-2020) the KWS Seed Quality Group has invested up to 10% of the overall budget allocated to production research into collaboration projects with RHUL.*" [S1].
Prof Leubner's work has **improved sugar beet seed production and product resilience** [S1]. This includes the delivery of pioneering molecular technology in the form of a novel diagnostic biomarker seed quality assay to reliably classify the dry seed's priming and storability status. The basic concept for this PCR assay was invented by Leubner in 2017 with molecular markers directly derived from the KWS-funded research (2013 to 2019), was further developed by KWS and was in 2018 filed as an invention disclosure [S1]. It is now part of the company's diagnostic capacity to evaluate sugar beet seed lot quality and resilience to ageing during storage. RHUL's EPOWER seed priming treatment with gas-plasma activated water (patent filed [S2]) is a novel environmental-friendly technology. In contrast to classical priming, it provides refined high-quality seed and retains storage resilience (Fig. B). In his role as expert consultant (2013 to 2020) Professor Leubner contributed with expert advice to internal discussions which led to KWS improving its priming and production processes, investing into novel technologies such as seed quality and automated germination assays, and **expanding the seed processing facilities** in 2019 for (together >EUR40,000,000) [S1]. Confidential reports of Annual Meetings contain Leubner's recommendations and changes to company procedures [S1]. These support KWS corporate strategy towards **greater sustainability in agriculture** and towards maintaining its world's leading position as sugar beet seed supplier.
Dr Steinbrecher's research has improved production processes and product resilience following the successful implementation of a novel quality control step in the sugar beet pelleting process [S3]. Seed pelleting is the application of material to convert the uneven size and shape of a seed into a uniform pellet (Fig. A), enabling machine planting. Pellets and pellet materials differ in their properties for which no test was available at KWS. An "*innovative and novel mechanical testing routine for sugar beet pellets*" [S3] was developed by Dr Steinbrecher during two feasibility studies (2016/2018). As a result of the successful projects, KWS invested in "*the acquisition of a new materials testing machine*" (02/2020), and in her role as consultant (2020), Dr Steinbrecher supported the implementation of the mechanical tests at the company. "***By implementing the protocols developed by Dr Steinbrecher we have added a new test to assess and evaluate our pellets in the production process.** Dr Steinbrecher will further contribute with expert knowledge on mechanical pellet testing to inform KWS sugar beet pellet quality.*" [S3]. KWS is committed to promoting sustainable, resource-efficient, and ecologically friendly farming with their products and thus research at Royal Holloway directly contributed to new agro-industrial practices.

Commercial benefit to Tozer Seeds

In the ISCF-funded Agri-Tech project on salad onion (*Allium*) seeds and a BBSRC-funded studentship with Tozer Seeds (2016 to 2020), RHUL developed innovative seed ageing assays [R5] and identified molecular markers for vegetable seed storability, ageing resilience and quality. RHUL identified a similar set of molecular ageing marker for Tozer's salad rocket seed during spaceflight [R6]. Tozer is one of the UK's leading independent vegetable and salad seed suppliers exporting all around the globe. These technologies have enabled implementation of **better seed quality control procedures** and improved monitoring of their warehouse seed storage and global commercial seed transport with container ships [S4]. Preliminary trial results in 2020 showed that the improved *Allium* seed quality is expected to provide a 30% increase in turnover corresponding to an expected increase in global market share from 8% to 10% [S4]. R&D Director Dr Frances Gawthrop states [S4]: "*The quality of our seed is of utmost importance to us. The collaboration with Royal Holloway has made a significant impact on our quality assurance procedures and has provided new assays that allowed us to increase our ability to test and maintain seed quality.*" Dr Gawthrop further explains:
"*Collaborating with RHUL has not only contributed to innovative monitoring technologies it has also encouraged us to expand our own R&D capacity. In March 2020, we opened our £500,000 in-house Innovation Centre and employed Matthew Walker, the iCASE PhD student from*

Leubner's group at Royal Holloway in the new role of Seed Quality Manager. This is a significant investment for Tozers. Our partnership with RHUL highlighted the need for more specialist in-house skills. The Innovation Centre and the Seed Quality Manager will help to underpin the continued expansion of the company by building on our tradition in breeding innovative vegetable varieties and in providing consistent quality seed and service. We have also employed another technician which has expanded our seed quality assay capacity by 20%." [S4].

(2) Increasing industry investment and generating employment
Europe (EU plus UK) is the world's leading exporter of high-quality crop seed and its expanding seed industry employs more than 50,000 people. Leubner and Steinbrecher's work has had a commercial impact on UK (Tozer Seeds) and international (KWS SAAT SE, EU-based headquarters) seed companies by informing their R&D strategies for **investments in new facilities**, improved production processes and quality control, and by employment of 7 (FTE) seed experts in the seed industry (including Tozer Seeds [S4]) plus further 12 former members of RHUL's Seed Science Research Group in other sectors [S5]. Overall, research at Royal Holloway **increased company revenues and cost savings**, R&D investment and employment in the area of crop seed quality and food security.

(3) Raising awareness for the importance of seed quality in food security
RHUL's research with rocket seeds contributed to the success of the **Rocket Science Project (**RSP) of the Royal Horticultural Society (2015, see pp. 23, 29-35 [S6]). The RSP was a stand-out highlight of the UK Space Agency's public 'Principia Campaign'. Tozer's salad rocket seeds were launched into space for six months on board the International Space Station with astronaut Tim Peake [S6]. Leubner's research demonstrated that the spaceflight caused seed ageing and revealed molecular biomarker for seed quality [R6]. According to the RSP Report [S6] and the Impact Assessment of the Campaign [S7] the RSP reached >8,500 schools and >600,000 pupils. ***"Royal Holloway working in conjunction with the UK Space Agency raised awareness for the importance of seed quality in food security*** *and contributed to pupils feeding their enthusiasm about plant science, food security and encouraged their interest in STEM."* [S8]. The UK Space Agency states about our publication [R6] and crop seed quality impact of RHUL's Seed Group: "*Everything we do in space has benefits for life on Earth. By understanding how space travel affects seed quality, we can begin to understand how to grow food on planet Earth, in hostile environments, with drought, heat stress or poor soils. Therefore, solutions to improve/preserve seed quality in space can lead to technologies to prolong shelf-life and ultimately to ensure food security. The findings demonstrate the importance of considering seed quality which is important in both space travel and for food security; especially considering the effects of climate change on planet Earth.*" [S8].
RHUL's Seed Group is currently expanding their reach by addressing food insecurity and the climate emergency in Sub-Saharan Africa, together with an Ethiopian partner network (funded by GCRF and supported by Syngenta Foundation) to implement EPOWER and the other innovative environmental-friendly seed technologies by 2025.

5. Sources to corroborate the impact

[**S1**] **Testimonial letter from KWS SAAT SE** for Prof Leubner (09.06.2020)
[**S2**] **"EPOWER - Gas Plasma Activated Water Seed Treatment"** filing by RHUL at UK Intellectual Property Office (UKIPO), patent application number 1916576.0, 14.11.2019.
[**S3**] **Testimonial letter from KWS SAAT SE** for Dr Steinbrecher (09.06.2020)
[**S4**] **Testimonial letter from Tozer Seeds** for Dr Steinbrecher and Prof Leubner (29.05.2020)
[**S5**] **PDF with names of 7 seed experts now working in the seed industry sector, plus 12 former members of RHUL's Seed Group who are employed by other sectors**
[**S6**] **Official Report of the Rocket Science Project (Royal Horticultural Society):** https://schoolgardening.rhs.org.uk/getmedia/a3385b8e-0eaf-4953-8d90-bc163ff0f982/Final-Rocket-Science-Report-Low-Res. Ref:p.10
[**S7**] **Impact Assessment of the Principia Campaign (UK Space Agency):** https://www.gov.uk/government/publications/impact-assessment-principia-campaign. Ref:p70
[**S8**] **Testimonial letter from the UK Space Agency** for Prof Leubner (18.09.2020)