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# Perennial grains for an Agroecological transition

Supporting the development of innovative value chain



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## TABLE

KEY FACTS.....	1
1. CONTEXT .....	1
2. OBJECTIVES OF DEVILCERPER R&D PROGRAM .....	3
Scientific objectives.....	3
Operational objectives.....	3
Partnership framework.....	3
Program structure.....	3
3. PRINCIPAL ADVANCES IN PLANT PHYSIOLOGY AND CROP PERFORMANCE .....	6
3.1 Action 1.1. Study of plant physiology and grain yield build-up .....	6
3.1.1 A growth strategy distinct from annual cereals.....	6
3.1.2 Tillering as a central adaptive mechanism.....	6
3.1.3 Resource allocation and stand architecture .....	8
3.1.4 Grain yield formation.....	9
3.1.5 Experiments and methods supporting action 1.....	9
3.2 Action 1.2 Environmental services provided by Intermediate wheatgrass.....	11
3.2.1 A deep and persistent root system.....	11
3.2.2 Environmental impacts and life cycle assessment.....	12
4. PRINCIPAL ADVANCES IN CROP MANAGEMENT .....	13
4.1 Action 2.1 Crop management .....	13
4.1.1 Response to nitrogen fertilization .....	13
4.1.2 Breeding progress and multi-environment evaluation.....	13
4.1.3 Cropping practices and technical management .....	15
4.2 Action 2.2 Farmers uses and objectives.....	15
4.2.1 Principal uses of intermediate wheatgrass expressed by French and North American farmers.....	15
4.2.2 Future actions : The development of a decision-support tool for crop performance assessment .....	16
4.2.3 Experiments and methods supporting action 22.....	19
5. PRINCIPAL ADVANCES IN GRAIN CHARACTERIZATION AND PROCESSING .....	20
5.1 Action 31. Grain composition .....	20
5.1.1 Grain physical structure .....	20
5.1.2 Chemical composition of grains.....	21

5.1.3 Post-harvest processing effects on grain quality.....	21
5.2 Action 32. Optimization of grain cleaning and dehulling processes.....	21
5.3 Action 33. Optimization of flour processing.....	22
5.4 Description of experimental procedures.....	24
6. RÉFÉRENCES.....	25

## KEY FACTS

Kernza crop management should be adapted according to its intended uses (see action 2.2) and the ecosystem services expected (see 1.2). European farmers are currently awaiting European regulation by EFSA and EU Commission

A comprehensive understanding of vegetative growth as well as reproductive processes and yield formation (see 1.1), to support the optimization of crop establishment and growth management practices

Further advances in the evaluation of ecosystem services (see 1.2) through a detailed analysis of root dynamics combined with a life cycle assessment (LCA) on production chain

A comprehensive assessment and optimization of cleaning/sorting, dehulling (see 3.2), and flour production technologies (see 3.3)

Nutritional and technological characteristics of Kernza™ demonstrated promising potential (see 3.1)

### 1. CONTEXT

Since the 1960s, agricultural intensification has substantially increased crop productivity but has also generated major environmental impacts, including nutrient leaching, pesticide contamination, soil degradation, and biodiversity loss. The specialization of farming systems around a limited number of highly productive crops (e.g. soft wheat, corn, soya) has further weakened ecosystem services and reduced the resilience of agricultural systems to climate change and economic uncertainties. In response to these challenges, the agroecological transition seeks to reconcile agricultural productivity with the preservation of natural resources through reduced reliance on synthetic inputs, improved resource-use efficiency, and enhanced system resilience. In this context, **perennial cereals represent a promising innovation** due to their ability to diversify cropping systems and maintain permanent soil cover.

Among these crops, Kernza™, developed from the domestication of intermediate wheatgrass (*Thinopyrum intermedium*) by the Land Institute (Kansas, USA), is the first commercially available perennial grain crop (see below the box). Since the 1990s, breeding programs have progressively improved Kernza™ yield performance through phenotypic selection and more recently with genomic selection approaches using genotyping-by-sequencing and genomic prediction. These advances have led to improvements in key agronomic traits, notably increased grain size and reduced seed shattering. Kernza™ also exhibits **several agroecological advantages**, including reduced nutrient leaching, enhanced carbon sequestration, permanent soil cover, and improved tolerance to temporary drought stress. However, **grain yield remains limited**, generally below 1 t. ha<sup>-1</sup>, with productivity declining over the production years. However, consumer interest in sustainable and regenerative agriculture is helping drive growth of the product market in North America (e.g., Sustain A Grain and Patagonia Provisions promotes different food products with Kernza™ like beers, breakfast cereals, pasta and crackers).

To improve crop productivity and stand persistence, several agronomic management strategies have been investigated, including sowing density and spatial arrangement, nitrogen fertilization, intercropping, defoliation management, weed control, stand thinning and crop termination practices.

In France, agronomic research on Kernza™ began at ISARA in 2016 through experimental trials and on-farm experiments (see **Picture 1**) carried out in partnership with INRAE, Gembloux Agro-Bio Tech and Arvalis institute. These studies generated advances in **understanding the physiological and ecological functioning of Kernza™** and defining agronomic management practices including crop establishment, nitrogen fertilization and weed control.



**Picture 1.** Plant growth and rooting system analysis of Kernza™ – July 2020  
Credit. Olivier Duchêne

Since 2020, a participatory research network involving approximately twenty farmers across France has enabled the evaluation of Kernza™ under a wide range of soil, climatic and agronomic conditions. This initiative has also provided valuable insights into farmer practices, uses and perceptions of the crop in France. Additional investigation also provides information from the USA where the market of Kernza™ -based products has been growing.

This initiative constitutes the **first participatory research program on perennial cereals in Europe** and aim to support the development of an innovative agroecological value chain based on perennial grain production. The overall objective of the program is to generate scientific and technical knowledge that can support farmers and contribute to the development of a regional Kernza™ production and processing sector in Europe.

More recently, the project has expanded to include additional research on **food processing and product valorization**. In particular, it aims to optimize grain cleaning, dehulling and milling processes in order to improve the technological and nutritional quality of Kernza. These efforts contribute to the development of technical recommendations and processing guidelines for both farmers and food processors.

Since 2023, this program has been affiliated with the ERC PERENNIAL led by Professor Olsson at Lund University. By combining research carried out in France and Sweden, the collaboration aims to **produce new insights into the development of value chains** involving a wide range of stakeholders, including farmers, processors, and other major public and private actors.

## 2. OBJECTIVES OF DEVILCERPER R&D PROGRAM

The DevilCerper program is organised around two complementary dimensions that integrate scientific research with operational development objectives.

### *Scientific objectives*

The scientific component aims to strengthen agronomic, ecological, and physiological knowledge of *Thinopyrum intermedium* in order to improve the understanding of crop dynamics under controlled and field conditions. Particular attention is devoted to the interactions between vegetative growth and reproductive development. Research activities focus on the analysis of tillering dynamics, soil cover development, and light interception, as well as on the relationships between vegetative and reproductive biomass and grain yield components. Additional work addresses grain composition and quality.

The program also explores the environmental services provided by perennial cropping systems, including reduced nutrient leaching reduction, biodiversity conservation, improved soil fertility, enhanced water and nutrient use efficiency, and carbon sequestration potential. These impacts are evaluated both directly through experimental trials and indirectly using life cycle assessment approaches.

### *Operational objectives*

The operational component of the program aims to develop practical recommendations for Kernza™ cultivation management. This includes optimizing crop establishment practices - such as sowing period, plant density, and spatial arrangement-, as well as nutrient and water management and weed control strategies. Another objective is to design-support tool enabling farmers to predict potential grain yield and adapt their management practices accordingly.

A further key objective is to enhance food processing and valorization pathways for Kernza™, particularly through the optimization of grain cleaning and dehulling processes to improve technological and nutritional quality. Together, these activities contribute to the development of technical guidelines and decision-support tools for both farmers and processors.

### *Partnership framework*

The program relies on a broad collaborative network involving organic and conventional farmers, research institutions engaged in both basic and applied research – such as INRAE and *Arvalis Institut du Végétal*- as well as companies including Alma Pro and JK Machinery. It also involves international research partners, notably The Land Institute and the Universities of Wisconsin–Madison, Cornell University, University of Minnesota, University of Manitoba, Lund University and Gembloux Agro-Bio Tech.

### *Program structure*

The program is organized into three complementary actions:

**Action 1 Plant performance under field conditions**, including the study of vegetative and reproductive development, grain yield formation, and the assessment of environmental services through direct measures and life cycle analysis.

**Action 2 Farming practices and crop management**, focusing on the analysis of agricultural practices, optimization of technical management strategies, and development of crop performance decision-support tools.

**Action 3 Grain quality and post-harvest processing**, covering the evaluation of nutritional and sanitary grain quality as well as the optimization of grain cleaning, dehulling and milling techniques with an emphasis on adapting processing methods.

## KERNZA™ IN FEW WORDS



*Thinopyrum intermedium*, commonly known as intermediate wheatgrass (IWG), is a perennial forage grass native to the Caucasus region. Initially introduced to North America as a forage species, intermediate wheatgrass is a perennial grass C3, hexaploid, and outcrossing species characterized by strong tillering capacity and tall plant stature (130 to 180 cm) with moderate rhizomatous growth. Its dense and deep fibrous root system promoting deep soil exploration, improved soil

structure, and efficient water and nutrient uptake (Clement et al., 2022). Root turnover is rapid, with strong dynamics of root production and decomposition. Phenologically, the species exhibits a dual floral induction requirement involving cold and short days followed by warm temperatures and long days, with a moderate vernalization requirement (Duchene et al., 2021).

The domestication of IWG as a grain crop began in the 1990s due to its agronomic characteristics favorable for grain production. The spikes are long and composed of 15–30 spikelets, each containing approximately 3–10 florets. Grains are small and elongated, with a thousand-kernel weight ranging from 4 to 10 g depending on environmental conditions (DeHaan et al., 2018; Wagoner and Schaeffer, 1990). From 2003, breeding strategies for IWG have significantly evolved from phenotypic selection to genomic selection using genotyping-by-sequencing and genomic prediction approaches to identify individuals for field evaluation (DeHaan et al., 2018). Breeding progress has notably improved grain size and reduced shattering risk (Bajgain et al., 2022; Stoll et al., 2024).

Commercialized under the trademark Kernza™, IWG exhibits several promising ecological characteristics. Compared with annual cereal crops, Kernza™ demonstrates greater tolerance to temporary drought events, improved long-term carbon sequestration capacity, and reduced nutrient leaching (Means et al., 2022). Nevertheless, grain productivity remains a major challenge. Grain yields are typically below 1 t ha<sup>-1</sup>, representing only 20–40% of the yield of extensively managed annual cereals, and yield declines markedly after the third year of production.

Over the last decade, different agronomic strategies have been investigated to improve crop performance, including optimization of sowing density and spatial arrangement, establishment timing, intercropping systems, nitrogen fertilization, defoliation management, weed control, application of growth regulators, stand thinning practices, and crop termination methods.

In France, agronomic research on IWG began in 2016 at ISARA within the Agroecology and Environment Research Unit. This initial research initiative led to the PhD work of Olivier Duchêne focusing on plant physiology and agronomic management. Subsequently, the CERPET project on crop management (National CASDAR funding) and the NAPERDIV project on plant–soil interactions (Biodiversa European funding) were conducted between 2020 and 2025, generating scientific and technical outputs.

Since 2020, a network of approximately twenty farmers distributed throughout France has enabled the evaluation of the crop under diverse soil, climatic and agronomic conditions. The PhD thesis of Christelle Ginot, completed in 2026, significantly improved knowledge both on plant behavior and on current and prospective farmer uses of the crop. Beyond scientific objectives, the program also aims to support the emergence of a new agroecological value chain based on perennial cereal crops, representing the first initiative of this kind in Europe.

### 3. PRINCIPAL ADVANCES IN PLANT PHYSIOLOGY AND CROP PERFORMANCE

#### 3.1 Action 1.1. Study of plant physiology and grain yield build-up

The research carried out within Action 1, largely based on the PhD work of Christelle Ginot (2026), has significantly advanced understanding of the ecophysiological functioning of Kernza™ (*Thinopyrum intermedium*). The research conducted within Action 1, mainly based on the PhD work of Christelle Ginot (2026), has significantly improved the understanding of the ecophysiological functioning of Kernza™ (*Thinopyrum intermedium*). These studies relied on semi-controlled trials and field experiments run between 2020 and 2025.

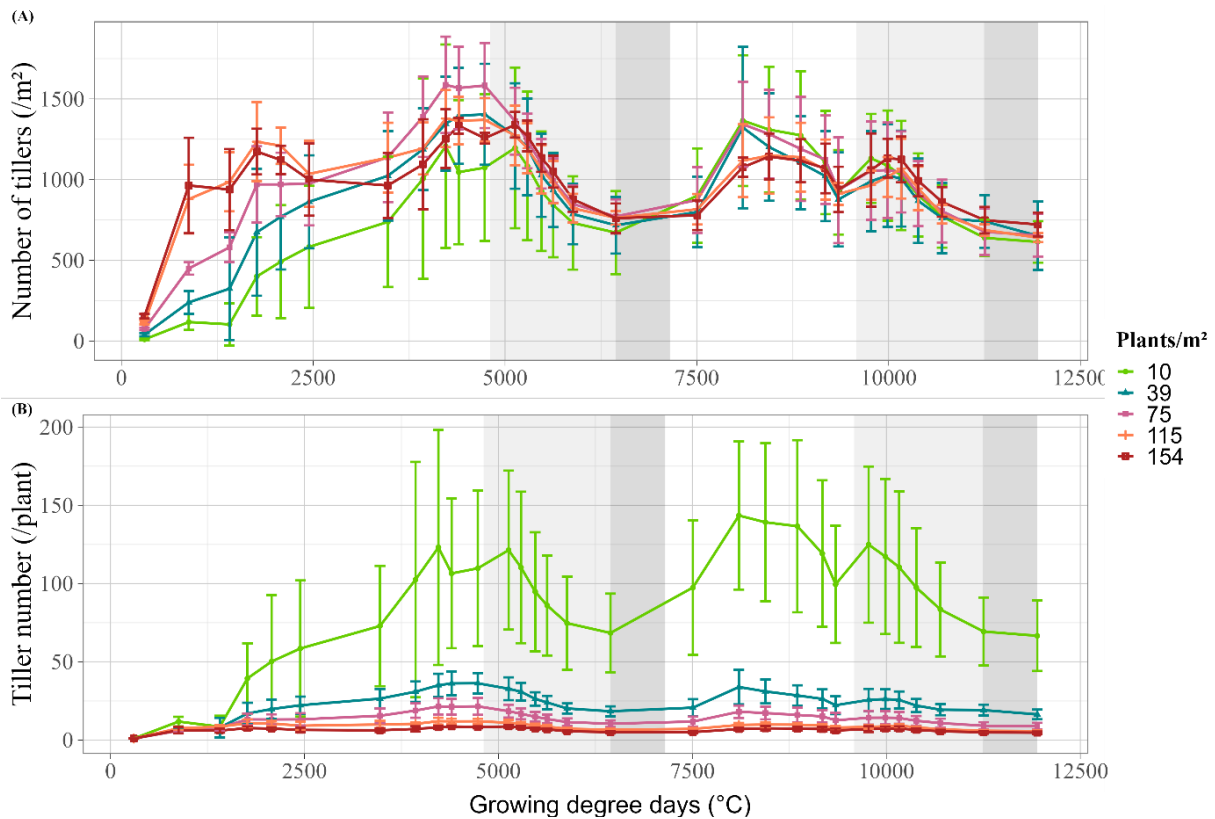
##### *3.1.1 A growth strategy distinct from annual cereals*

The results demonstrate that intermediate wheatgrass exhibits vegetative and reproductive behaviors fundamentally different from those of annual cereals like soft wheat largely produced in Western Europe. Grain yields remain low and highly variable depending on environmental and agronomic conditions, **averaging around 620 kg ha<sup>-1</sup>, with observed values ranging from 100 kg to 1.6 t ha<sup>-1</sup>**. The aboveground biomass varied in a similar range between **1.5 to 15.7 tons per hectare**. This large variability is associated with strong within-field heterogeneity in plant density, vigor, phenology, and plant characteristics.

The high plasticity of IWG is mainly related to the outcrossing and perennial nature of the species. Unlike annual cereals, which allocate most of their resources to reproduction at the end of the growing cycle, intermediate wheatgrass simultaneously maintains vegetative and reproductive functions. Resource allocation therefore involves trade-offs between growth, reproduction, and long-term survival, requiring multi-year evaluations to fully understand crop performance.

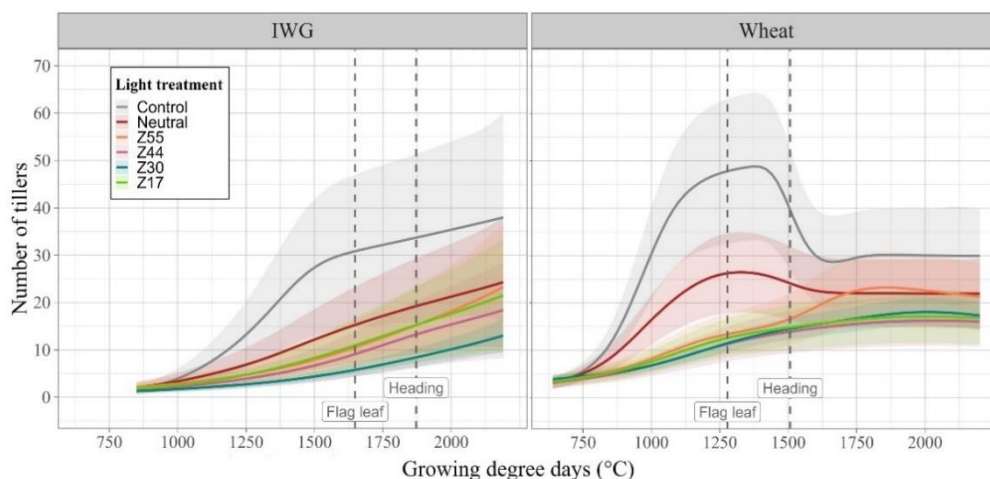
##### *3.1.2 Tillering as a central adaptive mechanism*

The experiment investigating plant density (10 to 150 plants/m<sup>2</sup>) and its effect on canopy development highlighted the **central role of tillering in crop adaptation**. Intermediate wheatgrass shows strong tillering plasticity (**Figure 1**), allowing the canopy to progressively close even at very low sowing densities (as low as 10 plants m<sup>-2</sup>). However, higher densities (> 100 plants m<sup>-2</sup>) enable earlier canopy closure, achieved after the 1<sup>st</sup> dual floral induction whereas low-density stands require a longer time to reach full canopy cover, increasing the risk of weed competition during the establishment phase.



**Figure 1.** Evolution of tiller density per m<sup>2</sup> (A) and per plant (B) for different plant densities (mean ± standard deviation). For each growing season, the light grey area represents the growth period from February 1st to flowering, extending to the end of June, and the dark grey area represents the period between flowering and physiological maturity. Field experiment conducted at the INRAE site in Clermont. (see Ginot et al, under review)

Tillering dynamics are strongly regulated by plant competition and light signaling, particularly the red to far-red light ratio (R:FR). A decrease in R:FR, characteristic of competitive light environments, progressively inhibits tiller emergence. Compared with wheat, the response of intermediate wheatgrass is more gradual, reflecting a distinct adaptive strategy to competition (Figure 2).



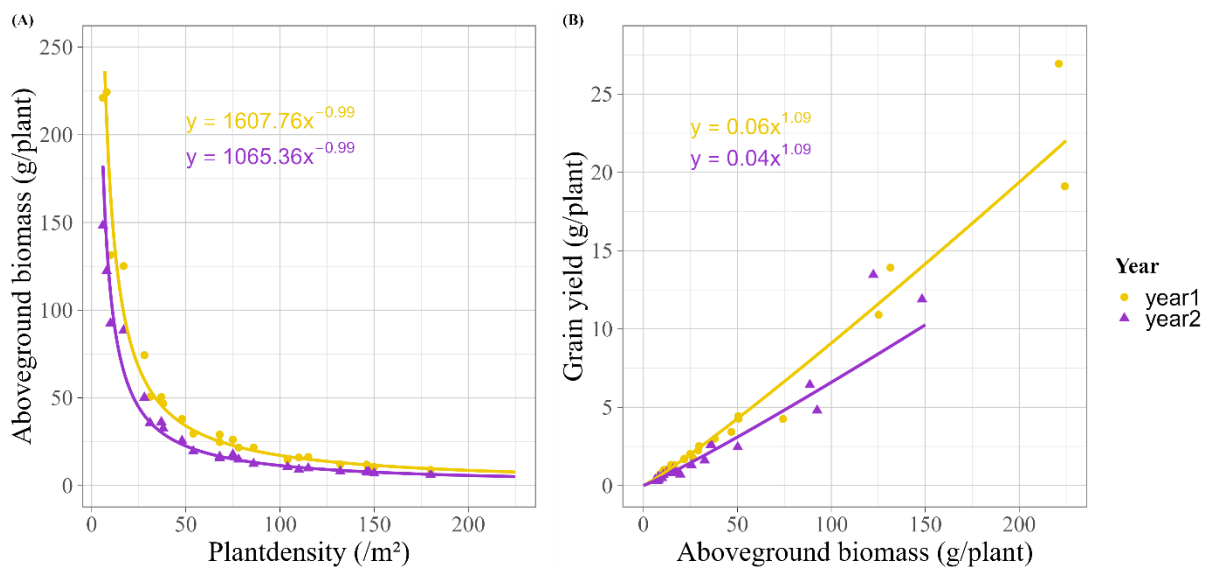
**Figure 1.** Evolution of the number of tillers per plant in intermediate wheatgrass (IWG) and wheat for plants subjected to different light treatments. The treatments 'Neutral', 'Z55', 'Z44', 'Z30', and 'Z17' allowed 28% of incident radiation to pass through, with a decreasing R:FR ratio: 1.09 (daylight), 0.55, 0.44, 0.30, and 0.17. The Control treatment allowed 96% of incident radiation to pass through with an R:FR ratio of 1.09, thereby enabling the separation of light quantity and quality effects. The curves shown were obtained using generalized additive models based on weekly tiller density measurements ( $n = 12 \times 6$  for each species). Semi-controlled experiment (tunnel conditions).

At low densities, plants develop more tillers, larger stature, and more robust vegetative structures. At high densities, early competition restricts individual tillering, although total tiller density per unit area tends to stabilize once canopy closure is achieved.

Although a reduction in tiller density per square meter was observed under field conditions during the reproductive phase—similar to what is seen in annual cereals—tunnel experiments showed a different pattern. When resources (water and nitrogen) were non-limiting and inter-plant competition was strongly reduced, tiller production did not cease after the onset of reproductive development. This continuous tillering complicates harvest management, as ear maturation becomes highly asynchronous over time. As a result, **grain ripening is spread out, increasing the risk of shattering and grain loss at harvest.**

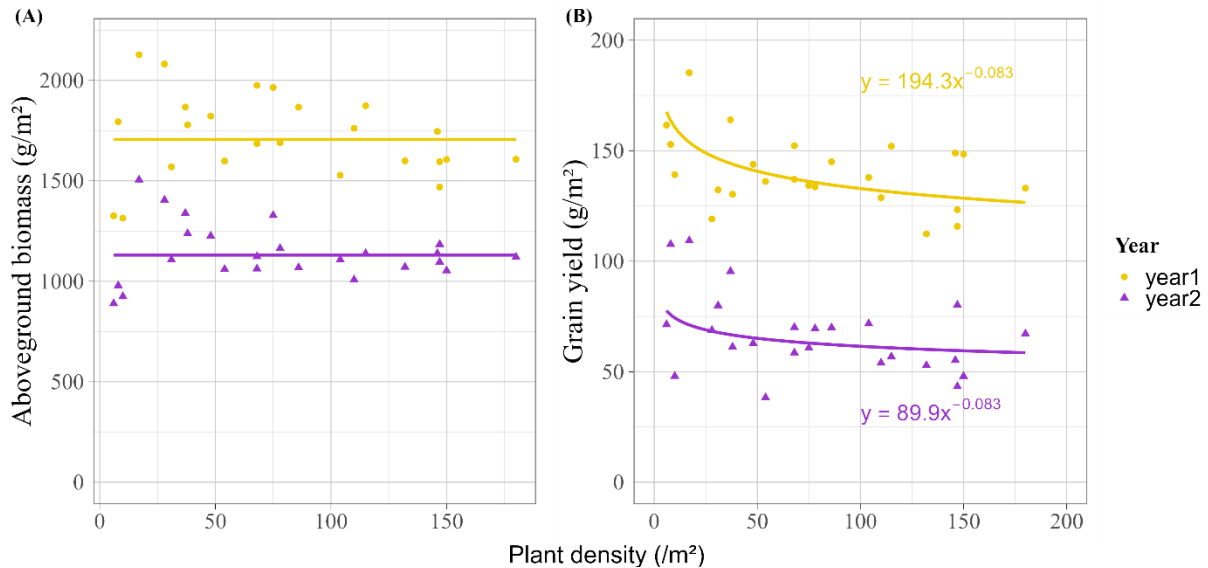
### 3.1.3 Resource allocation and stand architecture

The study showed that individual plant biomass increases sharply as sowing density decreases. Larger plants allocate proportionally more resources to reproduction, leading to increased harvest index and higher grain yield per plant (**Figure 3**).



**Figure 3.** Average plant size as a function of stand density (A), and grain yield per plant as a function of plant size (B), during the first and second harvest years. Field experiment at the INRAE site in Clermont.

At the stand scale, total aboveground biomass remains relatively stable across a broad range of sowing densities, consistent with the ecological theory of constant final yield. However, low-density stands improve light resource use and increase the proportion of biomass allocated both to grains and to perennial storage organs such as roots and crown tissues, which are essential for regrowth in subsequent years (**Figure 4**).



**Figure 4.** Aboveground biomass production (A) and grain yield (B) per unit area as a function of plant density. Field experiment at the INRAE site in Clermont.

These findings highlight the critical role of stand architecture in regulating grain yield, vegetative growth, and crop persistence. However, the relationships observed under controlled conditions should be further evaluated under field conditions, where both biotic and abiotic factors may influence crop performance.

### 3.1.4 Grain yield formation

As observed in annual cereals, grain yield in Kernza™ is strongly associated with grain number, primarily determined by the number of grains per spike and, to a lesser extent, by the number of fertile spikes (Fagnant et al 2024b). Low-density stands favor the development of larger and more fertile spikes, partially compensating for the lower spike density per unit area.

However, the physiological functioning of intermediate wheatgrass differs from annual cereals regarding assimilate remobilization. Evidence suggests that stem reserves contribute only marginally to grain filling. Spike photosynthesis appears to supply a major part of grain carbon demand for flowering and grain filling, while a substantial proportion of assimilates is retained in perennial organs in the basal internodes and rhizomes to support survival and regrowth (Reekie and Bazzaz, 1987). Consequently, severe stress affecting the spike during and after flowering (e.g., heat stress, disease pressure, or waterlogging) may substantially reduce grain yield and affect final grain weight.

This physiological strategy partly explains both the low grain productivity and the long-term persistence of the crop. It also highlights the strong sensitivity of grain yield to stresses affecting spikes during flowering and grain filling periods.

### 3.1.5 Experiments and methods supporting action 1

The results are based on a series of experiments conducted in France and Belgium between 2017 and 2025, combining agronomic field trials, semi-controlled experiments (tunnels, pots and partly field experiments without any water and nutrient deficiency), and ecophysiological studies on intermediate wheatgrass.

Early work conducted within the PhD of Olivier Duchêne (2017–2020) relied on five on-farm experimental sites in South East of France, managed under both organic and conventional

conditions, as well as a controlled experimental platform at Arvalis (Pusignan) (Duchene et al, 2020, 2021, 2023, 2024). These trials included variations in nitrogen fertilization and irrigation



regimes. They provided the first comprehensive characterization of the crop in France. Key findings highlighted the dynamics of root and shoot development, floral induction conditions, growth patterns, and yield components. A strong increase in biomass production between the two years of production was observed, reflecting improved resource acquisition and allocation capacity in the perennial system.

Complementary work conducted by PhD Laura Fagnant at Gembloux Agro-Bio Tech (Belgium) (Fagnant et al, 2023, 2024a, b, c, 2025) focused on nitrogen management and intercropping systems. Nitrogen fertilization experiments tested rates from 0 to 150 kg N ha<sup>-1</sup> and different application timings (early spring, mid-spring, and autumn). Additional trials evaluated associations between intermediate wheatgrass and forage legumes (white clover, red clover, and alfalfa), highlighting the importance of nutrient inputs and species interactions on system performance.



More recent experiments (2023–2025) at INRAE Clermont-Ferrand, coordinated by PhD Christelle Ginot, investigated the effects of plant density on canopy development and grain yield. Sowing densities ranged from 10 to 180 plants m<sup>-2</sup>. The study combined dynamic monitoring of canopy structure, light interception, tiller population, and biomass accumulation. Harvest analyses included

detailed yield components from 1 m<sup>2</sup> samples. The objectives were to understand tillering dynamics, test yield–density relationships, evaluate allometric trade-offs between vegetative and reproductive growth, and determine optimal plant density for grain production over two years.

A complementary semi-controlled experiment under tunnel at Clermont-Ferrand (2023) examined the role of light quality (red to far-red ratio) on tillering dynamics, comparing intermediate



**Picture 2.** Effect of light interception on tillering dynamics – July 2023  
Credit. Christelle Ginot

Additional studies included root system characterization under controlled conditions (Lyon, 2023), comparing multiple IWG accessions with forage and cereal reference species, as well as a multi-year field experiment (2022–2025) comparing different breeding cycles (TLI C5 vs TLI 801 vs older reference TLI C3) (**Picture 4**). These trials aimed to assess genotype performance, identify yield-limiting factors such as weed competition and abiotic stress, and evaluate the relevance of newly selected cultivars under production conditions.

wheatgrass with winter wheat. Results aimed to distinguish the effects of light intensity and spectral quality on tiller emergence, survival, phenology, and reproductive success (Weiner et al, 2004,2010) (**Picture 2**).



**Picture 4.** Root system dynamics and characterization – July 2024  
Credit. Robinson Durand

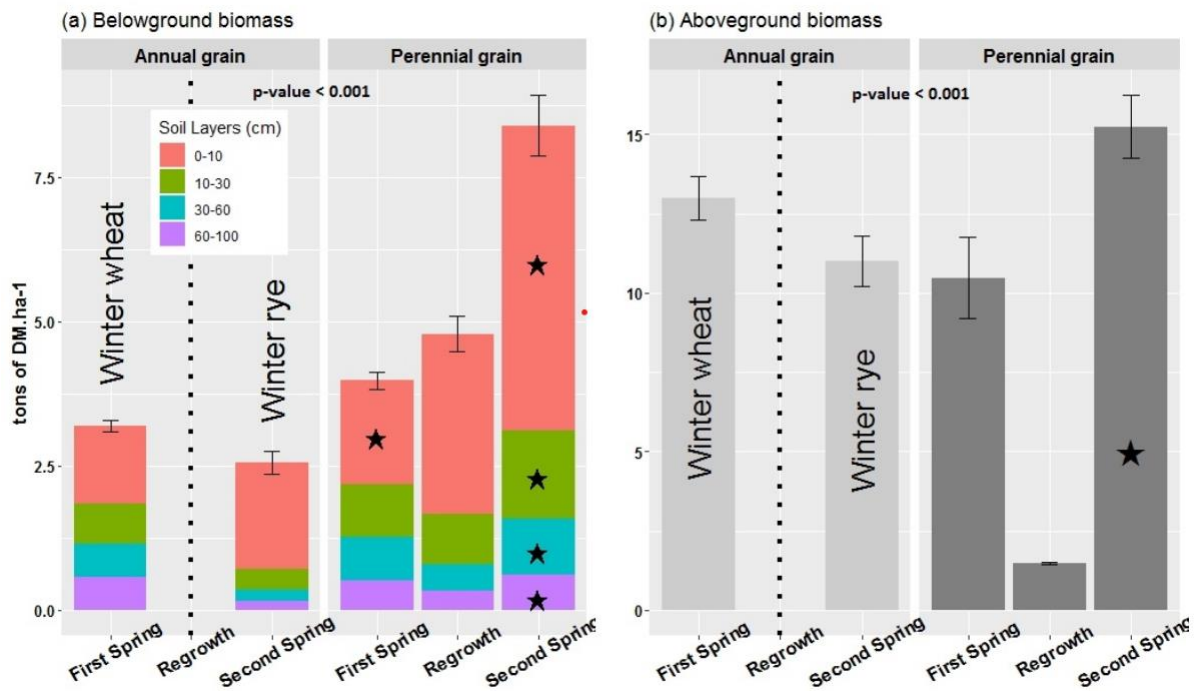
Overall, these studies provide a comprehensive understanding of IWG functioning across scales—from plant physiology to field performance—highlighting both its ecological benefits and current agronomic

### 3.2 Action 1.2 Environmental services provided by Intermediate wheatgrass

Research conducted between 2017 and 2025 significantly improved the understanding of the environmental functions provided by Kernza™ (*Thinopyrum intermedium*), particularly through studies on root systems, carbon and nitrogen dynamics, and life cycle assessment.

#### 3.2.1 A deep and persistent root system

Field and semi-controlled experiments demonstrated that intermediate wheatgrass rapidly develops a dense and deep root system, with a large proportion of biomass located in deeper soil layers from the second year onward. Compared with annual cereals, the crop allocates more resources belowground early in its development (**Figure 5**).



**Figure 5** Mean dry root biomass (a) and dry aboveground biomass (b) measured for annual and perennial cereals over two growing seasons. Statistical differences (post hoc analyses) between annual and perennial cereals are indicated by ★. Error bars represent standard errors for a soil depth ranging from 0 to 100 cm.

Root systems exhibit specific morphological traits, including larger root diameter, higher tissue density, and potentially longer lifespan. These characteristics indicate increased carbon allocation to perennial organs and suggest a strong contribution to soil structuring and carbon sequestration. Higher abundance of arbuscular mycorrhizal fungi in deeper soil layers further supports the crop's potential to stimulate soil biological activity.

Aboveground tissues are characterized by high silica content and a greater proportion of structural tissues, contributing to stand persistence and resistance to dry conditions, although partly reducing forage quality compared with temperate forage grasses.

### 3.2.2 Environmental impacts and life cycle assessment

The environmental impacts of intermediate wheatgrass production were assessed using the Life Cycle Assessment (LCA) method based on ISO 14040/44 standards (David et al., 2025a). The assessment was conducted on six farms — three managed under conventional agriculture and three under organic farming systems — where intermediate wheatgrass grown over three consecutive years was compared with a three-year rotation of annual crops including wheat, maize, rapeseed, and soybean, which are commonly cultivated in the South East of France.

The impacts evaluated, both annually and at the crop rotation scale, included 5 indicators as climate change, ozone depletion, water eutrophication, aquatic ecotoxicity, and acidification. Together, these indicators describe the effects of cropping systems on global warming and water resource protection.

The results showed that intermediate wheatgrass performed better when environmental impacts were expressed per hectare. Compared with annual cereals, the crop exhibited lower impacts across all indicators due to its perennial growth habit, limited soil disturbance restricted mainly to establishment, and reduced use of agricultural inputs. The positive effect of intermediate

wheatgrass on greenhouse gas emissions and climate change mitigation was clearly demonstrated. For example, the Global Warming Potential (GWP) indicator reached 682 kg CO<sub>2</sub> eq. per hectare for intermediate wheatgrass, compared with 1,477 to 3,012 kg CO<sub>2</sub> eq. per hectare depending on the annual crop considered. Similarly, the reduced use of synthetic inputs and pesticides significantly contributed to the protection of groundwater and surface water resources.

In contrast, intermediate wheatgrass was less efficient when impacts were expressed per tonne of grain produced, given that the average yield obtained in the study was only 600 kg ha<sup>-1</sup>. Grain yields of intermediate wheatgrass ranged from 150 to 900 kg ha<sup>-1</sup>, which remained much lower than those observed for annual crops, varying from 2.8 t ha<sup>-1</sup> for rapeseed to 9.3 t ha<sup>-1</sup> for maize. The low grain yield of intermediate wheatgrass therefore affects not only its economic performance but also its environmental performance per unit of production.

Nevertheless, the study highlighted the importance of increasing grain yield through breeding efforts in order to improve environmental performance per tonne produced. Increasing yield from 400 kg ha<sup>-1</sup> to 1 t ha<sup>-1</sup> reduced environmental impacts by 62% to 75%, depending on the indicator considered. An intermediate wheatgrass crop yielding 1 t ha<sup>-1</sup> — a level that may be achievable with recent accessions — could therefore reach an environmental impact comparable to that of wheat producing on average 6 t ha<sup>-1</sup>.

In conclusion, these findings confirm that intermediate wheatgrass is a **highly promising crop for enhancing soil carbon sequestration, reducing greenhouse gas emissions, and protecting both groundwater and surface water resources**, provided that grain yields continue to improve through advances in plant breeding and optimized crop management practices.

## 4. PRINCIPAL ADVANCES IN CROP MANAGEMENT

### 4.1 Action 2.1 Crop management

#### *4.1.1 Response to nitrogen fertilization*

Studies conducted at Gembloux Agro-Bio Tech demonstrated that intermediate wheatgrass responds positively to nitrogen fertilization, particularly through increased grain yield and grain protein concentration. However, the response quickly reaches a plateau and remains lower than that observed in wheat. The crop is also prone to lodging under excessive nitrogen supply because of its tall stature and dense tillering habit.

Critical nitrogen dilution curve defined by Fagnant et al (2003) revealed that intermediate wheatgrass has higher physiological nitrogen-use efficiency than wheat. The crop requires approximately 53–60% less nitrogen to produce equivalent aboveground biomass. In contrast, nitrogen-use efficiency for grain production remains low because a substantial proportion of absorbed nitrogen is stored in roots and basal stems to support regrowth in subsequent years.

The crop therefore operates through a multi-year strategy of nitrogen accumulation, storage, and internal remobilization, consistent with its perennial growth habit.

#### *4.1.2 Breeding progress and multi-environment evaluation*

Since 2003, intermediate wheatgrass breeding programs in North America, led primarily by the The Land Institute and the University of Minnesota, have substantially improved grain production potential per plant. Between 2003 and 2025, the Land Institute completed eleven recurrent

selection cycles targeting key domestication and agronomic traits, including grain yield, seed size, shattering resistance, and plant architecture. At ISARA, breeding evaluations began in 2017 using different materials (TLI C3, TLI C5, and TLI801 from The Land Institute, MN 1504 from University of Minnesota). Initial assessments consisted of comparative experimental trials conducted at INRAE Clermont-Ferrand and on a farm site, followed by subsequent on-farm experiments established across multiple locations.

From 2017 onward, the integration of genomic selection significantly accelerated genetic gain, enabling the development of five selection cycles within eight years (Crain et al., 2020). The breeding network expanded to Canada (University of Manitoba) in 2011 and subsequently to additional North American and European institutions (USDA programs, SLU in Sweden, and University of Copenhagen in Denmark), reflecting increasing international coordination of perennial grain improvement. Breeding objectives combine domestication traits with yield-determining agronomic traits, including increased grain size, enhanced spike fertility, higher proportion of free-threshing (naked) grains, reduced grain shattering, and reduced plant height to mitigate abiotic stress sensitivity. While domestication traits appear relatively stable across environments, agronomic traits show strong genotype  $\times$  environment interactions, particularly under contrasting pedo-climatic conditions.

The study developed in France aimed to identify germplasm adapted to French agro-ecosystems, which differ substantially from North American environments. Previous multi-year trials (2019–2022) conducted at INRAE Clermont-Ferrand compared TLI C3, TLI C5, and MN1504 (University of Minnesota, associated with the cultivar Clearwater, the first released perennial wheat variety in the United States), with and without intercropping with red clover. Across environments, no significant differences in grain yield were observed among genotypes, consistent with previous reports (DeHaan et al., 2018). In 2023–2024, ISARA and the Land Institute evaluated advanced germplasm, including TLI C5 and the genomic selection-derived synthetic population TLI801 (developed in 2019), in comparison with TLI C3. On-farm experiments were conducted across two adjacent fields over two growing seasons.

In the first year of evaluation, both advanced genotypes exhibited high vegetative development, with mean plant heights of 163–165 cm and aboveground biomass production ranging from 8.9 to 9.7 t DM ha<sup>-1</sup>. Canopy closure was rapid under 60 cm row spacing, although tiller density remained lower than that observed for TLI C3 in the reference network. Spike fertility was high (87–94%), partially compensating for reduced tillering, resulting in spike densities of 231–238 spikes m<sup>-2</sup>, approaching the mean values reported for TLI C3 (281 spikes m<sup>-2</sup>). Spike length was substantially increased (~30 cm), exceeding values previously recorded for TLI C3. Grain yield over 1 T per hectare surpassed the best performances of TLI C3 within the reference network. Thousand-kernel weight also increased, particularly for TLI801 (7–8 g compared with 6.6 g for TLI C3).

Results demonstrated significant improvements in recent materials with i) larger spikes and higher thousand-kernel weight, ii) improved proportion of free-threshing grains, iii) increased grain yield and iv) improved dehulling capacity for TLI801.

First-year yields exceeded the best performances previously obtained with TLIC3 material. However, crop performance remained highly dependent on climatic and agronomic constraints, including drought stress, heat stress, weed pressure, and declining spike fertility after the first production years. These results highlight the importance of multi-environment testing and adaptive management strategies for the deployment of IWG systems in Western Europe.



Despite these limitations, recent breeding advances confirm the strong potential for continued genetic improvement of this perennial grain crop, with yields range from 0.7 to 1.2 t ha<sup>-1</sup> of dehulled grain and harvest index of approximately 10%

### *4.1.3 Cropping practices and technical management*

Scientific and technical literature (DeHaan et al., 2023, 2025), including the Kernza® Grower Guide developed by the The Land Institute and the University of Minnesota, summarizes advances in crop management, including crop establishment, nitrogen nutrition via fertilization or intercropping, weed control, and harvesting. However, management practices must be adapted to local soil and climatic conditions, available equipment, labor constraints, and intended uses.

Participatory workshops conducted in 2022 within the on-farm network led to the definition of several prototype cropping systems, specifying (i) previous crops, (ii) establishment practices, (iii) fertilisation strategies, (iv) weed management, and (v) harvesting methods. More than ten crop management were developed to match farmers' objectives, integrating both strategic decisions (target uses) and tactical adjustments (field conditions and operational constraints), as described by Ginot et al. (2024).

## **4.2 Action 2.2 Farmers uses and objectives**

### *4.2.1 Principal uses of intermediate wheatgrass expressed by French and North American farmers*

A survey was conducted among 17 farmers from the on-farm network to identify the expected uses associated with integrating intermediate wheatgrass (Kernza™) into French farming systems (Ginot et al., 2024). Here, "uses" refer to the range of intended functions and anticipated benefits of cultivating the crop, including agricultural production, ecosystem services, and socio-economic outcomes (Bathelier et al, 2022, Wayman, Debray,et al, 2019). The study also aimed to understand how this crop is embedded within farmers' decision-making processes, linking expected uses to farm strategies and crop management practices. This analysis was further complemented by testimonies from North American Kernza® producers, presented in Ginot et al. (2026). In both France and the United States, farmers expressed a **wide diversity of expected uses, highlighting the multifunctional nature of the crop**. These expectations vary according to farm type (arable, mixed crop–livestock, or livestock systems), production mode (conventional or organic), and local socio-economic and agro-ecological conditions (Ginot et al., 2024).

At the farm scale, five main categories of expected uses were identified across both contexts:

1. **Valorisation of plant components through processing and market outlets:** Grain for human consumption was cited by all farmers and considered essential by a majority (70%) to guarantee added value. Livestock farmers and mixed systems also highlighted the potential use as forage, particularly under increasing drought conditions (53%). However, the development of viable feed markets remains a key prerequisite for arable farmers to adopt this use. Straw and biomass use (e.g., for anaerobic digestion) was also mentioned. Overall, the development of robust value chains is considered essential, as is regulatory recognition for human food use in Europe.
2. **Diversification crop for marginal or constrained fields:** Intermediate wheatgrass is perceived as a relevant option for low-fertility soils, biologically degraded areas, or fields with physical constraints such as slope and erosion risk. Its drought tolerance is a particularly valued trait in the context of climate change with increasing water deficits.
3. **Provision of agro-environmental services:** Soil quality and structure improvement were key motivations for French farmers (59%). North American farmers more frequently emphasized erosion control and soil fertility improvement (73%). The crop is valued for its deep root system, which contributes to soil structuring, erosion mitigation, and potential improvements in soil biological and physical fertility. Carbon sequestration was occasionally mentioned, particularly when linked to potential carbon credit schemes, although no concrete implementation was reported. Weed suppression was also cited due to high biomass production and groundcover, although its effectiveness remains uncertain.
4. **Reduction of mechanical costs and input use:** The perennial nature of the crop reduces the need for repeated field operations, thereby lowering labour requirements, machinery use, and synthetic input applications (fertilisers and pesticides), particularly during regrowth years (53% of responses).
5. **Innovation and engagement in agricultural transition:** Many farmers are motivated by the opportunity to experiment with an innovative cropping system and to contribute to agricultural transformation. Interaction with researchers is also perceived positively.

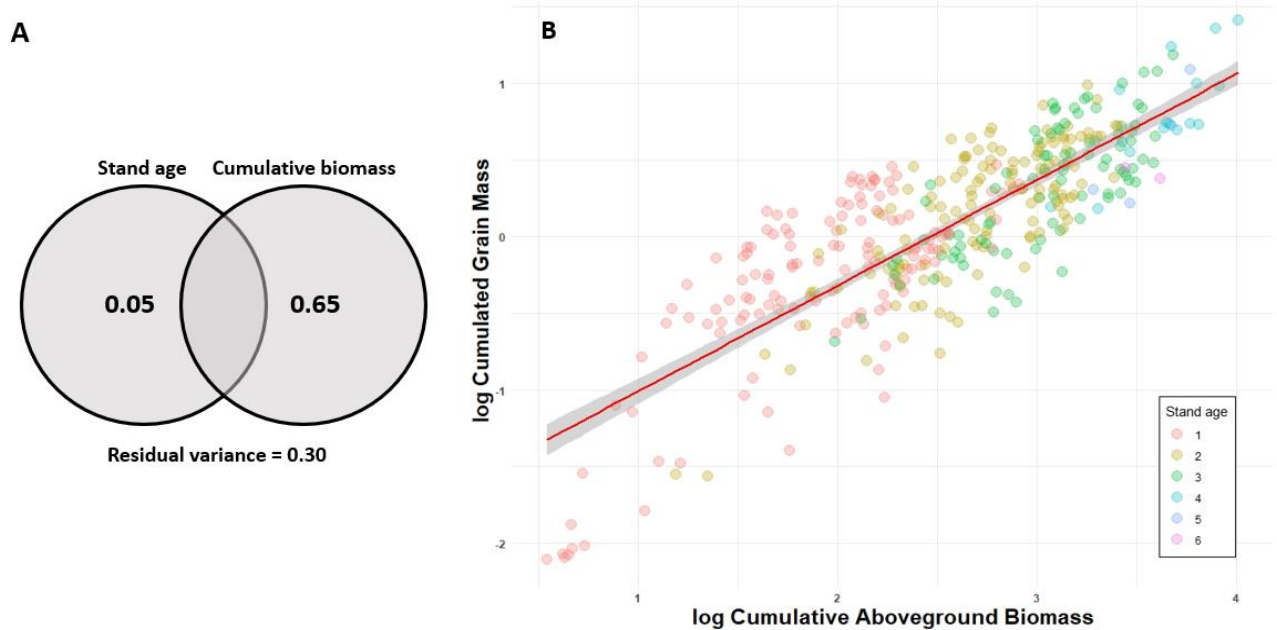
In addition, North American producers facing a growing market expressed broader socio-political motivations:

6. **Territorial engagement and public outreach:** Kernza™ cultivation is seen as a way to engage with local stakeholders, raise consumer awareness of sustainable agriculture, and strengthen local communities through events and farm-based activities.
7. **Alternative agricultural model:** Some producers view perennial grain systems as an alternative to dominant annual monocultures (e.g., maize–soybean systems), aiming to reinforce multifunctional agriculture, environmental stewardship, and farmer autonomy, while reducing dependence on purely economic drivers.

#### *4.2.2 Future actions : The development of a decision-support tool for crop performance assessment*

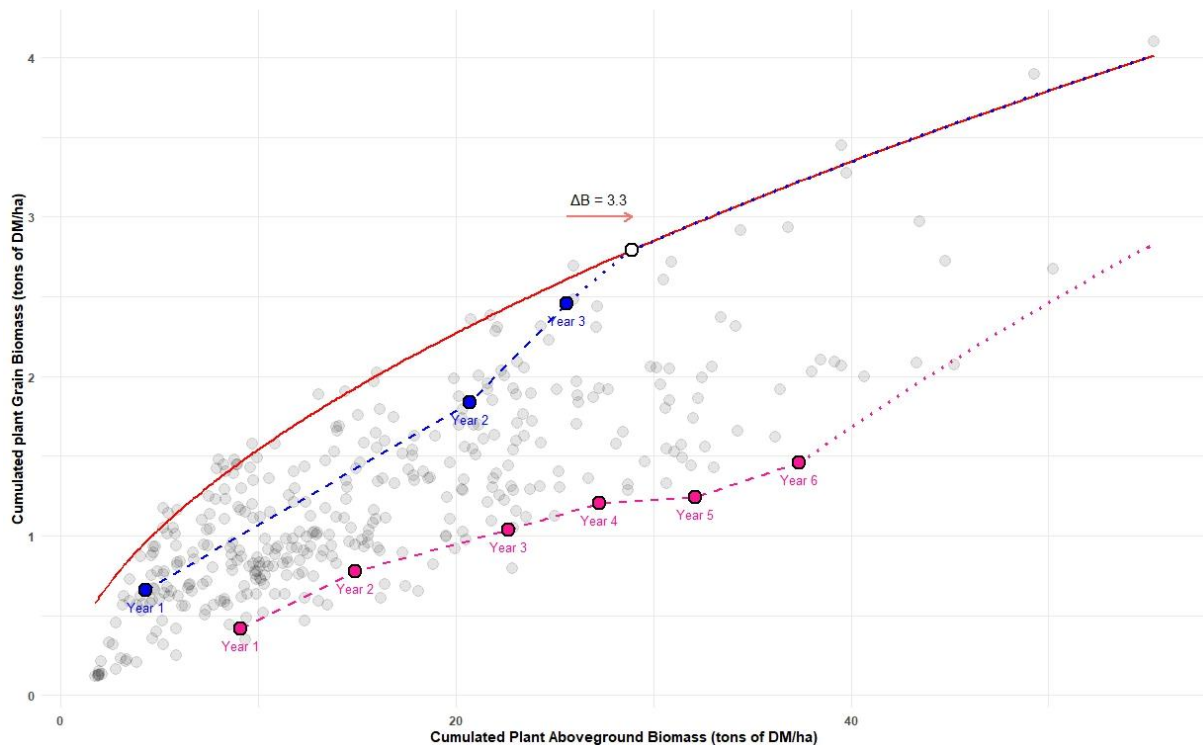
A comprehensive dataset collected since 2018 across 17 farms within the on-farm network, representing 72 production situations and up to six consecutive years of cultivation, was used to develop a diagnostic framework for intermediate wheatgrass performance. These multi-environment data, encompassing variation in location, climatic conditions, and management systems, allowed a global analysis of the relationship between grain production and aboveground biomass accumulation over time.

Results show that cumulative aboveground biomass is the primary driver of grain yield, explaining approximately 65% of observed variability, whereas stand age accounts for only about 5%. This indicates that biomass accumulation is a far more relevant indicator of stand performance than chronological age for characterizing perennial crop development. Nevertheless, substantial unexplained variability remains, reflecting environmental and biological factors affecting fertility and grain filling (**Figure 6**).



**Figure 6.** Variance partitioning of cumulative grain mass between stand age and cumulative aboveground biomass. (B) Relationships between cumulative grain mass and cumulative aboveground biomass, expressed in log-log values. The fitted line is described by  $y = -1.7 + 0.69x$  ( $R^2 = 0.67$ ).

The relationship between cumulative biomass and grain production follows an allometric scaling pattern. As biomass increases, grain yield also increases but in a non-linear manner, with a decreasing proportion of biomass allocated to reproductive structures. A minimum biomass threshold of approximately  $3 \text{ t ha}^{-1}$  was identified as necessary to initiate reproductive output, below which grain production remains negligible (**Figure 7**).



**Figure 7.** Expression of the performance trajectory into two production scenario observed among the 17 farms

The analysis also reveals an upper boundary to reproductive allocation. This allometric ceiling represents the maximum fraction of biomass that can be allocated to grain production at a given level of total biomass. This maximum declines with stand development, from approximately 22% in younger stands to around 7% in older stands, leading to a theoretical yield ceiling of approximately  $3.35 \text{ t ha}^{-1}$  for a total biomass of  $40 \text{ t ha}^{-1}$ .

This allometric framework provides a practical decision-support tool for identifying the main constraints on yield build-up. Low productivity may result either from insufficient biomass accumulation (e.g., due to nutrient or water limitations or poor establishment) or from suboptimal reproductive allocation (e.g., stress during critical developmental stages or genetic constraints). This approach therefore extends beyond site- or year-specific interpretations by offering a generalized framework for understanding growth–yield relationships in intermediate wheatgrass systems.

Within this framework, distinct developmental trajectories can be identified. Some stands, affected by early constraints such as poor establishment or recurrent stress, accumulate limited biomass and remain persistently low yielding. Others may initially perform below potential but can shift towards higher productivity trajectories under improved conditions. However, this recovery potential is constrained by an intrinsic physiological limit on annual reproductive allocation.

These dynamics are largely driven by ecological and density-dependent processes. In young stands, canopy structure and plant density strongly influence resource partitioning; low density tends to favour larger plants with higher reproductive allocation. In contrast, in older, denser stands, increased competition and canopy closure reduce light availability and limit investment in grain production. Consequently, as cumulative biomass increases, reproductive effort becomes progressively lower and more stable.

The decline in reproductive allocation with stand age reflects an adaptive strategy characteristic of perennial species. Over time, plants increasingly allocate resources to vegetative structures such as roots, rhizomes, and storage organs, enhancing persistence and competitive ability, at the expense of grain production. This trade-off is not solely a physiological limitation but represents an evolutionary strategy adapted to variable environments.

### 4.2.3 Experiments and methods supporting action 22



Picture 6. On-farm network of Kernza™ – July 2020  
Credit: Christophe David

This work is based on qualitative on-farm research conducted in France and the United States to understand the development, management, and potential uses of intermediate wheatgrass (Kernza™).

In France, the study relied on a national network of farmers established in 2020 (Picture 6). The methodology combined semi-structured individual interviews with farmers and collective workshops. First, 17 individual interviews were conducted with farmers from the national observation network to document their farming systems, objectives, management practices,

- Organic farms
- Conventional farms
- Farms under conversion to organic

perceptions of intermediate wheatgrass, and expectations regarding its future development. These interviews also served to prepare the subsequent workshops by gathering farmers' knowledge and expectations.

Second, two participatory workshops were organized in 2022 with 9 of the interviewed farmers. These workshops focused on (i) discussing economic viability and financial drivers of the crop, (ii) designing cropping systems integrating intermediate wheatgrass, and (iii) co-developing technical management practices. Participation was restricted to farmers only to avoid bias and ensure farmer-led reflection.

In the United States, the study involved 16 semi-structured interviews with farmers growing Kernza™ mainly in Minnesota and Wisconsin, the regions with the largest cultivated areas in 2024. The interviews, conducted in early 2024, explored farm history and structure, agricultural practices, socio-economic context, and farmers' motivations for adopting Kernza™. A final section of each interview addressed research and breeding priorities.

Overall, both studies used qualitative, farmer-centered approaches combining interviews and participatory methods to characterize production systems, practices, and perceptions surrounding intermediate wheatgrass in different socio-economic contexts.

## 5. PRINCIPAL ADVANCES IN GRAIN CHARACTERIZATION AND PROCESSING

### 5.1 Action 31. Grain composition

The physical structure of intermediate wheatgrass (Kernza™) grain, including kernel size and the proportion of outer bran layers, directly influences its chemical composition as well as its technological and nutritional properties. Kernza™ is characterized by a high protein content (>15 g/100 g), high dietary fibre content (>20 g/100 g), elevated ash content (>2.5 g/100 g), moderate lipid content (~3 g/100 g), and the presence of bioactive compounds such as carotenoids and hydroxycinnamic acids (Tyl and Ismail, 2019; EFSA NDA, 2025). These attributes **confer notable nutritional and functional potential for food applications**.

However, certain characteristics can limit technological performance in specific end-use products, particularly bread-making. For example, low levels of damaged starch and reduced proportions of high-molecular-weight glutenin subunits (HMW-GS) (Rahardjo et al., 2018) negatively affect dough elasticity and loaf volume for bread-type products. Conversely, the lower abundance of HMW-GS is partially offset by relatively higher proportions of  $\alpha$ -,  $\beta$ -, and  $\gamma$ -gliadins and low-molecular-weight glutenins (LMW-GS), which may be advantageous for pasta-type products. Thus, the specific protein composition of Kernza™ determines functional properties that must be adapted according to the intended end-use (e.g., bread, pasta, flakes).

The high proportion of bran relative to the small endosperm fraction results in a lower gluten-forming potential. Consequently, the limited gluten network of Kernza™ flour may be improved through gluten addition (e.g., vital gluten or gluten isolates) or blending with stronger soft or durum wheat flours.

Grain chemical composition is influenced by both agronomic conditions and post-harvest processing. Crop management and plant nutrition directly affect protein and fiber contents, thereby influencing the rheological and technological properties of derived products. Post-harvest operations such as cleaning and dehulling also have a major impact on nutritional quality, processing performance, and sensory attributes.

The objective of Action 3 is therefore to further characterize the technological and nutritional properties of grains produced in France and to assess their processing suitability. A secondary objective is to optimize cleaning and dehulling procedures in order to improve both economic efficiency and flour quality, while minimizing material losses and evaluating the potential valorization of by-products.

#### 5.1.1 Grain physical structure

Kernza® grains are characterized by multiple bran layers, a small embryo, and a low thousand-kernel weight (5–7 g compared with 42–54 g in bread wheat). This is mainly due to limited grain dimensions (approximately 5–6 mm in length and 1.0–1.2 mm in thickness, compared with ~2.5 mm thickness in wheat) (Picture 7). The high ratio of bran to endosperm and embryo largely explains the observed chemical composition.



**Picture 7.** Representation of Kernza grains a and b and wheat grains (hard red wheat type) from Banjade et al. (2019a).

### 5.1.2 Chemical composition of grains

Data from five experimental trials conducted between 2019 and 2021 at the Arvalis Boigneville laboratory were compared with reference values for bread wheat (OECD, 2023). Grain moisture content at harvest remained stable across environments (from 12 to 14.5%).

Kernza™ grain showed a high ash content, exceeding 2.5% of dry matter, which is substantially higher than that observed in bread wheat (1.5–1.8%). This difference is mainly explained by the larger proportion of bran relative to endosperm in Kernza™. Protein content ranged from 12 to 18 g per 100 g, generally higher than in bread soft wheat (10–13 g per 100 g), although lower than some values previously reported in the literature (14–23 g per 100 g).

The starch content of Kernza™ grain was consistently low, remaining below 45%, whereas bread wheat typically contains between 58 and 69% starch. This reduced starch concentration reflects the smaller endosperm fraction of the grain. In contrast, fibre content was higher in Kernza™ (15–21%) than in wheat (11–18%), again consistent with the higher bran proportion. Lipid content was also greater in Kernza™, ranging from 2.4 to 2.8%, compared with less than 2% in bread wheat.

No major compositional differences were observed among the TLI C3, TLI C5, and MN1504 genotypes under controlled conditions. Overall, Kernza™ grain contains less starch than bread soft wheat but exhibits a superior nutritional profile, particularly due to its higher protein, fiber, and lipid contents.

### 5.1.3 Post-harvest processing effects on grain quality

Due to its high bran content, Kernza™ grain generally requires dehulling regardless of the intended end use. Laboratory dehulling tests conducted on reference samples (David et al., 2025b) demonstrated that processing increased the relative protein content, reduced ash content, increased the starch proportion, and improved the homogeneity of processed grain lots.

Previous studies have also shown that dehulling decreases insoluble fibre content while improving dough extensibility and bread specific volume (Banjade et al., 2019). These results highlight the importance of considering not only agronomic conditions but also post-harvest operations, such as dehulling and milling, when assessing final product quality.

The high nutritional value of Kernza™ grain is largely associated with the presence of fibre in the bran, lipids in the germ, and carotenoids. However, its protein composition, particularly the low proportion of high-molecular-weight glutenins combined with limited starch availability, restricts dough viscoelastic properties and consequently limits baking performance (Banjade et al., 2019).

## 5.2 Action 32. Optimization of grain cleaning and dehulling processes

The efficiency of grain cleaning and dehulling directly **influences both the technological quality and the economic value of the final product**. The objectives of this work were therefore to i) reduce potential microbial and physical contamination, ii) ensure technological, nutritional, and sensory quality of the final product in accordance with consumer expectations, and iii) improve the economic value of the grain through optimization of post-harvest processing operations.

Most previous studies on Kernza™ post-harvest processing have been conducted under laboratory conditions. The present work aimed to develop an industrial-scale pilot process suitable for future implementation by farmer groups, cooperatives, or independent processors.

A first collaboration was established with the Alma Pro company between March 2023 and March 2024 to optimize grain cleaning, dehulling, and milling procedures. Eleven experimental lots were conducted using a US1500 dehuller, an M10 grain sorter, and a MELIA30 stone mill.

The results obtained from the 11 experimental lots **revealed substantial variability associated with harvest and production conditions**, particularly weed contamination at harvest. Average grain extraction rates after sorting and dehulling **reached approximately 61%**, exceeding the values generally reported in the United States (30–50%; AURI, University of Minnesota, 2022).

However, improving extraction efficiency required substantial processing time, with average capacities of approximately **190 kg h<sup>-1</sup> for dehulling and 50 kg h<sup>-1</sup> for sorting**. These results highlight the trade-off between extraction efficiency and operational throughput.

This work was subsequently extended from 2024 to early 2026 using an industrial pilot unit, partially funded through the European research initiative Perennial coordinated by Lennart Olsson at Lund University. **The pilot installation included a JHC 03 dehuller and a JCC 05 sorting unit manufactured by JK Machinery, together with a prototype stone mill developed in collaboration with Alma Pro.** The objective was to evaluate processing performance under contrasting operational conditions, including variations in grain type and moisture content.

Trials conducted under semi-controlled conditions (heated buildings with grain moisture adjustment) showed substantially **higher extraction efficiencies, reaching up to 76% with an average of 57%**. In contrast, extraction efficiency **declined markedly under uncontrolled humidity conditions from 27 to 33%**, confirming the critical importance of grain moisture management during post-harvest operations. These findings indicate that humidity control, both within the grain and in the processing environment, is essential to ensure optimal dehulling and sorting performance.

Increasing extraction efficiency is particularly important given the relatively low field productivity of Kernza™, where economic value strongly depends on maximizing usable grain recovery while preserving flour technological and nutritional quality.

### 5.3 Action 33. Optimization of flour processing

Four flour production trials were conducted using a stone mill (Melia30, 30 cm millstones, Alma Pro, **Picture 8**) to preserve flour nutritional quality. Milling tests performed on dehulled Kernza™ grains resulted in **extraction rates ranging from 36% to 49% (Table 1)**. These extraction yields remain lower than those typically achieved for wheat flour (60–62%).

**Picture 8.** Mélia 30 stone mill (30 cm millstone diameter) manufactured by Alma Pro. Photo credit: ISARA.



Flour Trial	1	2	3	4
Temperature (°C)	16.0	18.9	21.0	21.9
Relative Humidity (%)	52	56	53	51
Throughput (kg h <sup>-1</sup> )	6.4	12.6	9.9	10.3
	kg	%	kg	%
Particle size < 180 µm	3.76	33.6	0.63	31.3
180–224 µm	0.51	4.6	0.05	2.5
224–350 µm	0.25	2.2	0.05	2.5
> 350 µm	6.34	56.7	1.04	51.7
Extraction yield (< 350 µm)	4.52	40.4	0.73	36.3
Stone losses	0.06	0.5	0.09	4.5
Sieve losses	0.27	2.4	0.14	7.0

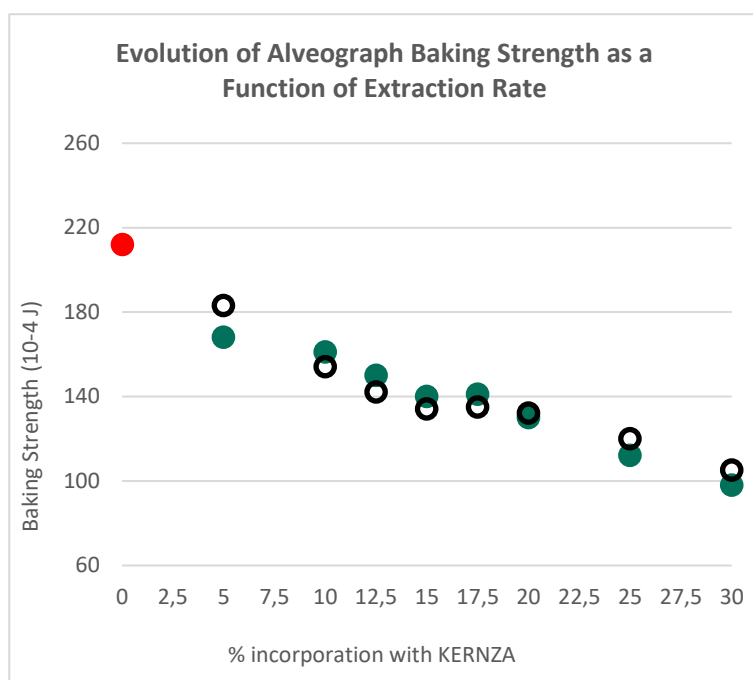
**Table 1.** Milling characteristics, particle-size distribution, and extraction yields obtained from dehulled Kernza™ grain fractions using a stone mill.

The high lipid content of Kernza™ grains created significant processing challenges, particularly mill clogging during grinding. To mitigate this issue, the milling process was modified by introducing a pulsed air injection system. Subsequent pilot-scale trials conducted in early 2026 confirmed these difficulties, highlighting that **lipid-rich grains can increase milling temperature**, thereby exacerbating clogging risks and **potentially accelerating flour oxidation**. The temperature in the flour manufacturing building must be continuously monitored and controlled to prevent any additional temperature rise, thereby limiting any reduction in extraction yield and minimizing the risk of oxidation.

Mineral analysis showed that flours produced from dehulled grains had **lower ash contents** than those obtained from whole grains. Their ash levels were comparable to those of wheat flours classified as T65–T80, making them **potentially suitable for breadmaking applications**. Previous studies have also demonstrated that blending Kernza™ flour with wheat flour can **enhance nutritional quality** through higher carotenoid and antioxidant contents while contributing desirable yellow pigmentation and distinctive sensory characteristics.

Despite relatively high protein concentrations, Kernza™ flour exhibits **limited breadmaking performance**. Earlier studies have shown that its protein composition is characterized by a low proportion of high-molecular-weight glutenins and a high fiber content, resulting in a weaker gluten network than that of bread wheat.

To assess its technological potential, two blends containing 0–30% Kernza™ were evaluated and compared with one reference (100% of soft wheat). Increasing incorporation rates led to a progressive decline in dough strength, with a reduction of at least 40 alveograph units even at low inclusion levels (**Figure 8**). At 30% incorporation, dough strength fell to approximately 100 alveograph units, a level generally considered unsuitable for conventional breadmaking. This deterioration was primarily associated with reduced dough tenacity and elasticity, while extensibility remained relatively unaffected.



Overall, although Kernza™ offers attractive nutritional and sensory properties, its protein profile limits its suitability for traditional breadmaking. Successful use in wheat-based bakery products would require adapted processing techniques (Cetiner et al, 2023). Alternatively, Kernza™ flour may be better suited to products that rely less on gas retention and gluten network formation, such as biscuits, crackers, pasta, flakes, or brewing applications.

**Figure 8.** Evolution of baking strength using one reference flour of soft wheat (BS equal to 220) with two flours types

Future product development should therefore consider not only processing performance but also consumer acceptance and the economic value of the final products.

## 5.4 Description of experimental procedures

### Nutritional and technological analysis of grains and flours

The objective of this work was to characterize the physical properties and chemical composition of grain samples collected from farmer's fields within the observation network, as well as from experimental stations managed by Arvalis and INRAE. The diversity of production environments enabled assessment of sample variability and crop homogeneity under contrasting agronomic conditions.

Eleven grain lots harvested between 2019 and 2021 were analyzed using certified laboratory methods. Analyses included:

- thousand-kernel weight (NF EN ISO 520),
- ash content (NF EN ISO 2171),
- protein concentration using the Dumas method (NF EN ISO 16634-2),
- lipid content (NF EN ISO 11085; Randall method),
- starch content using the Ewers polarimetric method (CEE Regulation 152/2009).

Flour samples produced during Action 33 were further characterized for:

- protein and ash content,
- protein aggregate distribution using SE-HPLC,
- dough viscoelastic properties using the Chopin alveograph (NF EN ISO 27971),
- water absorption and rheological behaviour during mixing using Mixolab analysis (NF V03-765),
- baking performance using the standard French bread-making test (NF V03-716).

These standardized analytical methods are commonly used in France for the technological characterization of cereal grains and flour functionality.

## Optimization of cleaning and dehulling operations

The optimization process aimed to improve grain cleaning, dehulling, and flour production while ensuring both technological quality and economic profitability. Initial optimization work was conducted with Alma Pro, a family-owned cereal processing company located in Saint-Donat-sur-l'Herbasse (France). This work was subsequently extended using the industrial pilot unit located on an organic farm within the regional experimental network (Isère department, France).

The processing sequence consisted of four main stages:

- **Step 0 (optional):** preliminary grain cleaning using the JCC 05 sorter when high impurity levels were present.
- **Step 1:** dehulling using the JHC 03 dehuller, generating fractions of dehulled/non-dehulled grains and hull residues.
- **Step 2:** sorting of processed grains through the JCC 05 sorter to separate large grains, small grains, hulls, dust, and impurities.
- **Step 3:** secondary sorting to further improve grain purity and reduce residual hull contamination.
- **Step 4:** flour production using the MELIA30 stone mill, generating flour fractions of different particle sizes.

Progressive optimization of the sorting process included the development of eight customized sorting screens and modifications to impurity extraction systems in order to improve flour quality and reduce undesirable mineral particles responsible for sandy mouthfeel defects.

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