Legume Generation

Boosting innovation in breeding for the next generation of legume crops for Europe

Progressing the breeding of lentil

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Legume Generation Report 12

Legume Generation (Boosting innovation in breeding for the next generation of legume crops for Europe) has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No.101081329. It also receives support from the governments of the United Kingdom, Switzerland and New Zealand.

Legume Generation

Legume Generation (Boosting innovation in breeding for the next generation of legume crops for Europe) is an innovation action funded by the European Union through Horizon Europe under grant agreement 101081329. It also receives support from the governments of the United Kingdom, Switzerland and New Zealand. The Legume Generation consortium comprises 33 partners in 15 countries.

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Citation

Please cite this report as follows:

Ninou, E., Mylonas, I., Murphy-Bokern, D., Hennenkaemper, U., Jeanson, P., di Vittorio, V., Papa, R., Gioia, T. and Lohwasser, U., 2026. Progressing the breeding of lentil. Legume Generation Report 12. Available from www.legumegeneration.eu and www.legumehub.eu. DOI: https://doi.org/10.5281/zenodo.21507074

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Contents

Summary

This report sets out the progress made in boosting the breeding of lentil in the first 24 months of the Legume Generation project. It describes the establishment and progress of the Lentil Innovation Community (IC); the harmonisation of phenotyping protocols across Europe; the completion of the first cycle of multi-environment field trials; the launch of the second validation cycle; and the initiation of breeding tools and early demonstration activities.

The Lentil IC brings together partners from Greece, Italy, France, Germany, and the Netherlands in a coordinated platform for data, seed, and knowledge exchange. This collaboration with germplasm mainly from IPK, ICARDA, and information and lines from other previous projects such as INCREASE, Linsel, and other initiatives was assembled to broaden the narrow genetic base of lentil cultivated in Europe. Key breeding priorities included yield, drought tolerance, earliness, seed quality, yield stability, cold tolerance, and disease resistance.

A major focus of our work is the phenotypic evaluation of lentil genetic resources across contrasting European environments. In trial cycle 1, around 600 accessions were evaluated across sites in Greece, Germany, France, and Italy using a common descriptor list based on UPOV/CPVO standards. These revealed substantial diversity for important agronomic and quality traits. The best-performing accessions were selected and entered into a second cycle of validation trials across Greece, Germany, and Italy to confirm their performance and adaptability. At the same time, progress was made in breeding methods and tools. SSD line development, single-plant selection, and molecular diversity analysis were initiated to support the creation of improved breeding material.

Although the first composite crossing attempts were affected by high temperatures, parental material was successfully maintained for renewed crossing in the following season. In parallel, digital phenotyping was introduced on a pilot basis in Greece through drone-based imaging, aiming to improve field evaluation accuracy. We also started early demonstration activities in Germany, where breeding lines and varieties were tested under field conditions and presented during a farmer field day.

Overall, we have established a strong foundation for the next phase of work, providing harmonised phenotypic data, validated germplasm, and the first breeding resources needed for the development of improved lentil cultivars for Europe. Newly developed genotypes are demonstrating improved yield stability, tolerance to major diseases, and increased resilience to drought, heat, and cold. These advances strengthen competitiveness with other crops and reduce dependence on imports. Our work is particularly relevant to organic farming systems where lentil has great potential - high-protein, high-quality cultivars are being advanced to supply the expanding plant-based (protein) food market, pathways are created for value-added products such as lentil-based snacks, flours, and meat substitutes. We are harnessing diverse genetic resources, including landraces and composite cross populations, to generate cultivars tailored to specific climatic zones and market niches; training activities are equipping breeders and farmers with expertise in phenotyping, seed-quality assessment, and digital agronomy tools, while reinforcing public–private collaboration to ensure the sustainability of

innovation outputs. All these activities provide a solid foundation for a more resilient and market-oriented European lentil sector, supported by strengthened seed supply chains and improved farm-level profitability.

Introduction

Lentils are among the most important pulse crops worldwide, highly valued for their exceptional nutritional profile, including high protein content, vitamins, minerals, and fibre, while being naturally free of fat or cholesterol. Compared with many other grain legumes, lentils hold a superior position for their nutritional quality and suitability for human consumption.[1] In addition, they are particularly important for their adaptability under low-input conditions or organic farming systems and in environments with limited water availability.[2] These characteristics make lentils well suited for sustainable cropping systems, especially in Mediterranean and semi-arid regions. In recent years, interest in lentil cultivation has also increased in Central Europe[3] where they are considered a promising option for diversifying cropping systems and improving their economic stability under the increasing frequency of climate-related stresses. Consumption is rising in Europe, but supply relies heavily on imports, primarily from outside Europe (e.g., Canada). Local production is hindered by the scarcity of well-adapted varieties, limited investment in breeding, and weak connections between research and commercial practice.

Legume Generation provides the framework for the establishment of the Lentil Innovation Community (IC), which was developed to address existing gaps in lentil breeding and cultivation by linking breeders, researchers, farmers, and industry within a coordinated breeding network. The IC brings together partners from Greece, Italy, France, Germany, and the Netherlands, each contributing with specialised expertise in phenotyping, genotyping, stress physiology, and breeding for both conventional and organic systems. The basic aim is to develop cultivars tailored to Europe’s diverse agro-environments, meeting farmers’ needs, market demands, and sustainability goals.

The Lentil Innovation Community

The Lentil Innovation Community (Lentil IC), established at the start of the project, aims to facilitate the efficient exchange of data and knowledge among partners. Initial activities focused on the systematic aggregation of information from previous national and international lentil breeding programmes and projects, including seeds exchange from IPK, ICARDA, and regional research initiatives.

The diversity of lentil varieties cultivated in Europe is very limited; therefore, it was necessary to integrate existing knowledge, methodology and germplasm resources from INCREASE, Linsel, LentilBreed, ICARDA, and the IPK Genebank. To broaden the genetic base, a large number of accessions were collected, mainly from the ICARDA and IPK gene banks. Phenotyping protocols were harmonised among participating institutions to ensure

[1] https://plants.sc.egov.usda.gov/DocumentLibrary/plantguide/pdf/pg_lecu2.pdf
[2] https://doi.org/10.1016/j.eja.2026.128061
[3] Divéky-Ertsey, A.; Gál, I.; Madaras, K.; Pusztai, P.; Csambalik, L. Contribution of Pulses to Agrobiodiversity in the View of EU Protein Strategy. Stresses 2022, 2, 90-112. https://doi.org/10.3390/stresses2010008

comparable and standardised evaluations. In parallel, UNIBAS initiated the development of SSD lines from 15 heterogeneous accessions provided by IHU, under controlled greenhouse conditions in Potenza, Italy, to accelerate the creation of uniform breeding material.

Key traits identified for prioritisation for northern and southern Europe included drought tolerance, productivity, seed quality characteristics, early maturity, and yield stability resistance to fusarium wilt and ascochyta blight and cold tolerance. Phenotypic evaluation protocols were harmonised across partner institutions and encompassed standardised field trials across diverse agro-ecological zones and trait-specific scoring systems. These protocols enabled consistent and comparable data collection on morphological, agronomic, and disease-resistance traits across multiple environments and breeding pipelines.

UNIBAS developed genetically purified lentil lines from the heterogeneous accession under controlled conditions (i.e., insect free) to obtain SSD lines. 15 heterogeneous accessions were received from partners and were sown in the experimental greenhouse of UNIBAS in Potenza, southern Italy (latitude 40°38′51.7″N, longitude 15°48′31.7″E). Sowing was performed on 24 January 2025. Two seeds per accession were sown into 24 cm (diameter) × 26 cm (height) pots. After germination a plant was removed from the pot. All plants were irrigated regularly three times per day with 400 ml of tap water. The experiment was carried out under natural lighting, with an air temperature kept between 18 and 22 °C, and a relative humidity between 40 and 60%. The multiplication cycle is ongoing (*Figure 1*).

Figure 1. SSD experiments carried out by UNIBAS, Potenza, Italy.

Phenotyping lentil

During the first year, multi-location field trials were conducted across six sites in Greece, France, Germany, and Italy, followed by a second year of trials across five sites in Greece, Germany, and Italy. In the first year, approximately 600 accessions were evaluated, including IPK landraces, ICARDA accessions, INCREASE SSD lines, and locally adapted material. Based on the first-year results, around 150 accessions were selected for evaluation in the second-year validation trials. A common descriptor list based on UPOV/CPVO standards was applied across all locations, covering phenology, yield, plant architecture, seed characteristics, and disease resistance (Table 1). A harmonised data collection framework was established and preliminary analyses revealed substantial diversity in yield potential, expressed as seed weight / m^2, flowering time, maturity from the plants' emergence cotyledon and testa (seed coat) colour, and thousand-kernel weight.

Regarding partner contributions, IHU coordinated the activities, managed the data, and evaluated approximately 400 accessions in Greece (Figure 2). IPK provided around 200 landraces and conducted replicated trials in Germany (*Figure 3*). Keyserlingk carried out organic trials using IPK and ICARDA accessions and locally bred material (Figure 4). LIDEA evaluated 180 accessions for industrial and quality traits (
Figure 5), while UNIBAS tested 160 SSD lines derived from the INCREASE collection (Figure 6). UNIVPM prepared material for nutritional and technological analyses, SRU contributed to the design of genotype panels targeting heat tolerance, and ESKUSA supported the alignment of trials with commercial production requirements.

Cycle 1
Substantial progress has been made in evaluating lentil genetic resources through a coordinated, multi-partner effort under diverse environmental conditions across northern and southern Europe. The primary objective is to characterise phenotypic variation across a broad panel of lentil accessions, with the aim of identifying promising genotypes for boosting lentil breeding through improved breeding lines. Where homogenous lines were used (available from previous projects, e.g., SSD lines from INCREASE), we used this phenotyping to test their performance under field conditions.

The germplasm distribution and trial implementation included approximately 190 landrace accessions from IPK were distributed among core partners: 190 accessions to IHU (Greece), 100 to KEY (Germany), 100 to IPK (Germany) and 182 to LIDEA (France), with some overlap (approximately 100 accessions) to facilitate cross-site comparison and data integration. Additional accessions from ICARDA and breeding lines from individual partners were also included in the germplasm collection. IHU evaluated 220 additional accessions form ICARDA and 20 local germplasm. KEY evaluated additionally as 128 additional lines from internal and ICARDA sources. UNIBAS in Italy evaluated under field conditions 160 lentil lines selected within the INCREASE collection, to confirm their productivity under field conditions.

Field trials were conducted across six locations—Greece (2 sites), France, Germany (2 sites), and Italy—representing diverse agro-ecological zones. Commercial lentil varieties were used as checks. Plot sizes ranged from 0.5 to 2 m², and all data referred to yield/m^2 phenotypic evaluations followed a harmonised protocol agreed upon by Lentil IC members where the descriptors lists of UPOV were taken into account (Table 1).

Table 1. The common descriptors characteristics used for lentil phenotyping

Descriptor – Stage	Description / Notes
Filed establishment	
Sowing date	Date when seeds were sown
Emerging Date	Date when seedlings emerged
Germination (%)	Percentage of seeds that germinated
Seed: Cotyledon colour	1 = Yellow, 2 = Green to greenish yellow, 3 = Orange to red
Anthesis	
Plant: Anthocyanin colouration	0 = Absent, 1 = Present
Plant: Growth habit	1 = Prostrate, 2 = Semi-erect, 3 = Erect
Plant: Homogeneity	1 = Very heterogeneous, 3 = Slightly heterogeneous, 5 = Moderately homogeneous, 7 = Very homogeneous, 9 = Completely homogeneous
Flower: Standard colour (Petal)	1 = White, 2 = Pink, 3 = Blue
Flower: Violet stripes on standard	1 = Absent, 9 = Present
Flower: Start of flowering	Date when flowering begins
Plant: Plant height (cm)	At 50% flowering stage
Flower: 50% flowering date	Date when 50% of plants are flowering
Flower: Flowers per node	1 = Only one, 2 = One or two, 3 = Only two, 4 = Two or three, 5 = Only three, 6 = More than three
Pod setting – Seed development	
Height of first pod (cm)	Measured from ground to first pod
First ripe pods date	Date of first ripe pods
Seeds per pod	1 = One, 2 = Two, 3 = Three
Stability / lodging	1 = Standing, 2 = Mixed, 3 = Lying
Ripening homogeneity	1 = Very heterogeneous, 3 = Slightly heterogeneous, 5 = Moderately homogeneous, 7 = Very homogeneous, 9 = Completely homogeneous
Pod shattering	1 = non-shattering, 2 = Partially shattering, 3 = Fully shattering
Seed: Seed coat colour (Testa)	1 = Greenish yellow, 2 = Green, 3 = Pink, 4 = Black
Seed: Seed pattern	0 = Absent, 1 = Blotched, 2 = Spotted, 3 = Marbled, 4 = Marbled and blotched
Seed: Seed weight	Seed weight should be measured on at least two samples of 100 seeds. Immature and infected seeds should be excluded
1000 Seed weight (TKM)	Weight of 1000 seeds
Seed: Seed length	Length of individual seeds
Seed: Seed width	Width of individual seeds
Seed: Seed area	Surface area of individual seeds
Yield	
Harvest date	Date when plants were harvested
Yield	Harvested weight or productivity
Non-marketable Lentils (%)	Percentage of lentils considered unfit for market (seed quality)
Remarks / diseases	Observations, notes on plant health or abnormalities

Figure 2. Phenotypic evaluation of 400 lentil accessions in IHU, Greece 2023-2024

Figure 3. Lentils accessions phenotyping in IPK, Germany 2023-2024

Figure 4. Lentils accessions phenotyping in KEY, Germany, 2023-2024.

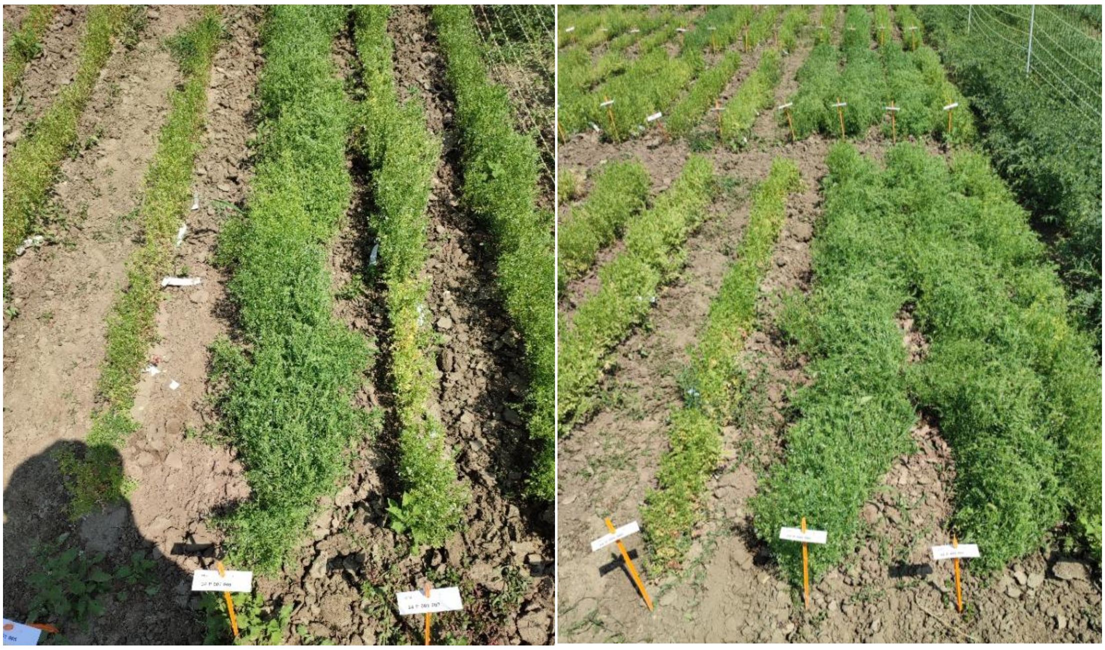


Figure 5. Lentils phenotyping of accessions in LIDEA, France 2023-2024.

Figure 6. Field experiment in UNIBAS of SSD lines phenotyping developed from previous research, some SSD lines derived from accessions that are in common, Italy 2023-2024.

Common descriptors were agreed based on previous experience, official descriptor lists (UPOV, CPVO) and work; this enables to phenotype in a common way. The descriptor list includes the grouping characteristics as agreed in UPOV (seed cotyledon colour, flower standard colour, flowering time, seed colour and weight).

Data processing and harmonisation included a standardised phenotypic characterisation format that was established in collaboration with Lentil IC members. Initial data from the 2023–2024 season are being processed, with preliminary analyses underway to identify trends in performance, adaptation, and trait heritability.

Preliminary phenotyping results

The general average yield in IPK across the accessions was 77 g/m^2. Notably, some of the accessions produced very low or even zero yields, a testament that there was minimal adaptation to the specific cultivation conditions of the IPK field trial in some accessions (Figure 7).

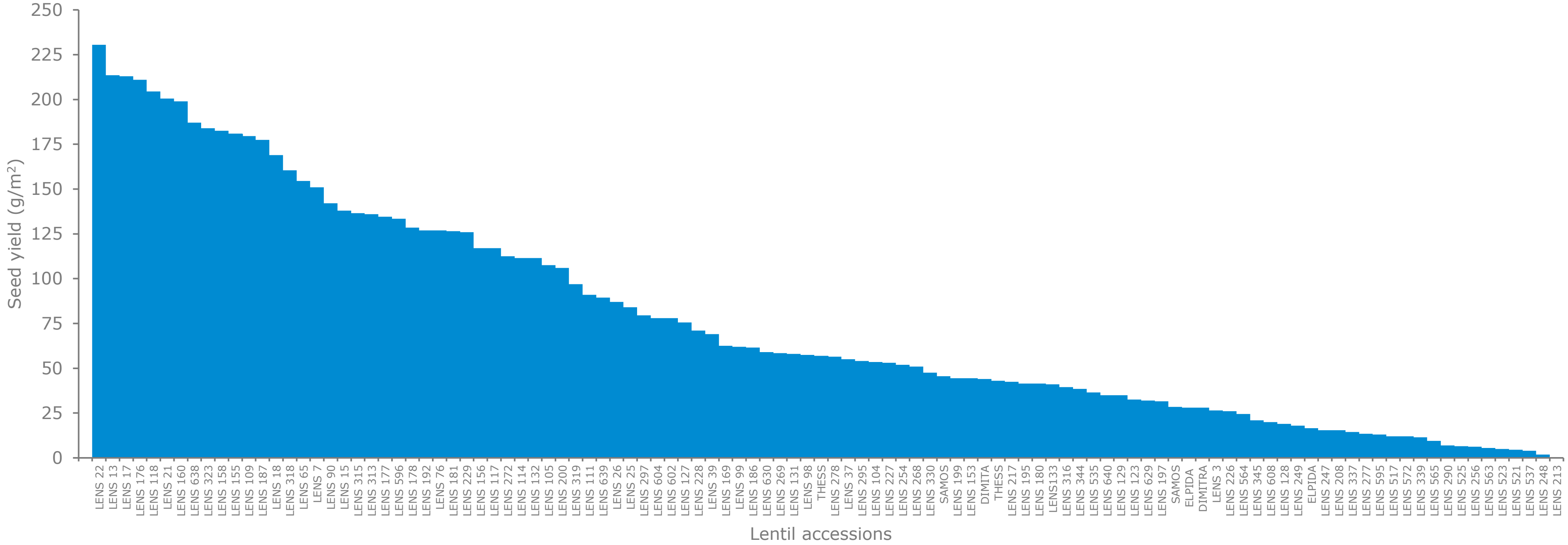


Figure 7. Seed yield of accessions (grams per m^2) evaluated during 2023-24 cropping season in IPK.

Such accessions were likely to not respond positively to the local soil, climatic factors, or agricultural management measures applied during the trial. In contrast, one subgroup of approximately 26 accessions performed clearly better with yields that were more than 25% above the experimental mean. This indicates the high degree of genetic diversity within the population, combined with individual genotype yield potential for performance under the existing environmental and management conditions at the IPK. This type of information is particularly valuable for breeders wishing to encourage yield stability and responsiveness.

The flowering time interval of the lentil accessions ranged from 39 to 56 days from plants emergence, and this is representative of considerable genetic variation for this phenological trait, which correlates highly with earliness. Earliness is a key adaptive trait in lentil breeding, especially in Mediterranean and semi-arid environments, as it facilitates escape from terminal drought and heat stress.[4][5] Early-flowering accessions complete their life cycle before the onset of late-season extremes, thereby reducing adverse effects on crop development, seed filling, and yield stability.

The observed mean flowering time was 54 days - close to the highest of 56 days - indicating that most of the accessions tended to flower rather late (Figure 8). Nevertheless, twelve stood out by flowering extremely early - 8 to 15 days before the mean. Out of these, five accessions (LENS 13, LENS 17, LENS 109, LENS 118, and LENS 160) not only flowered early but also maintained high level of yield, making them potential targets for future genetic improvement and climate-resilient breeding in the future (Figure 9).

[4] Kumar, J., & Srivastava, E. (2015), https://doi.org/10.18805/lr.v38i4.6620

[5] Al Noor, M., Sarker, A., Erskine, W., & others. (2024). *Plants, 13*(16), 2345. https://doi.org/10.3390/plants13162345

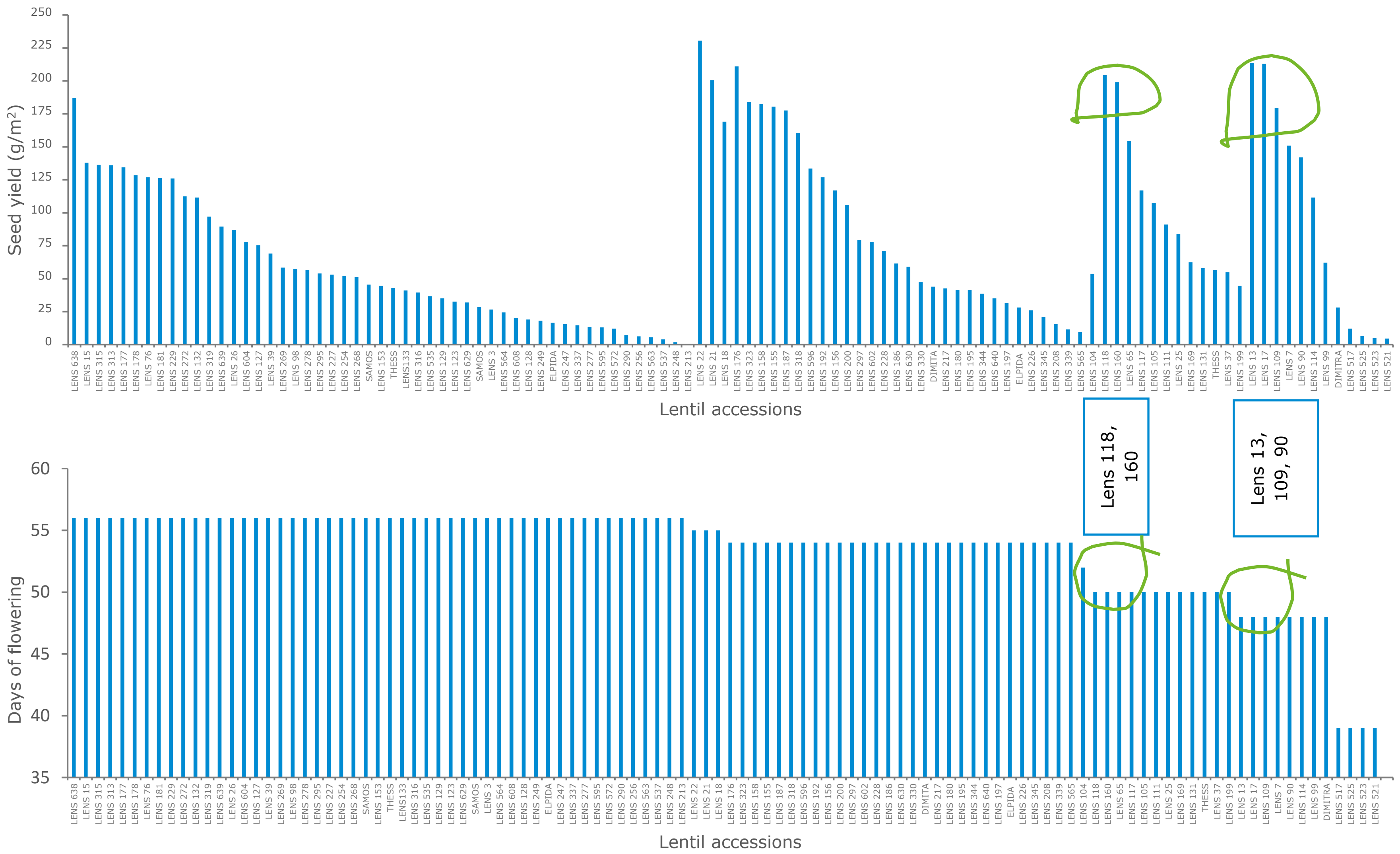


Figure 8. Date of flowering from emergence regarding the seed yield (g/m^2) of accessions evaluated during 2023-24 cropping season in IPK.

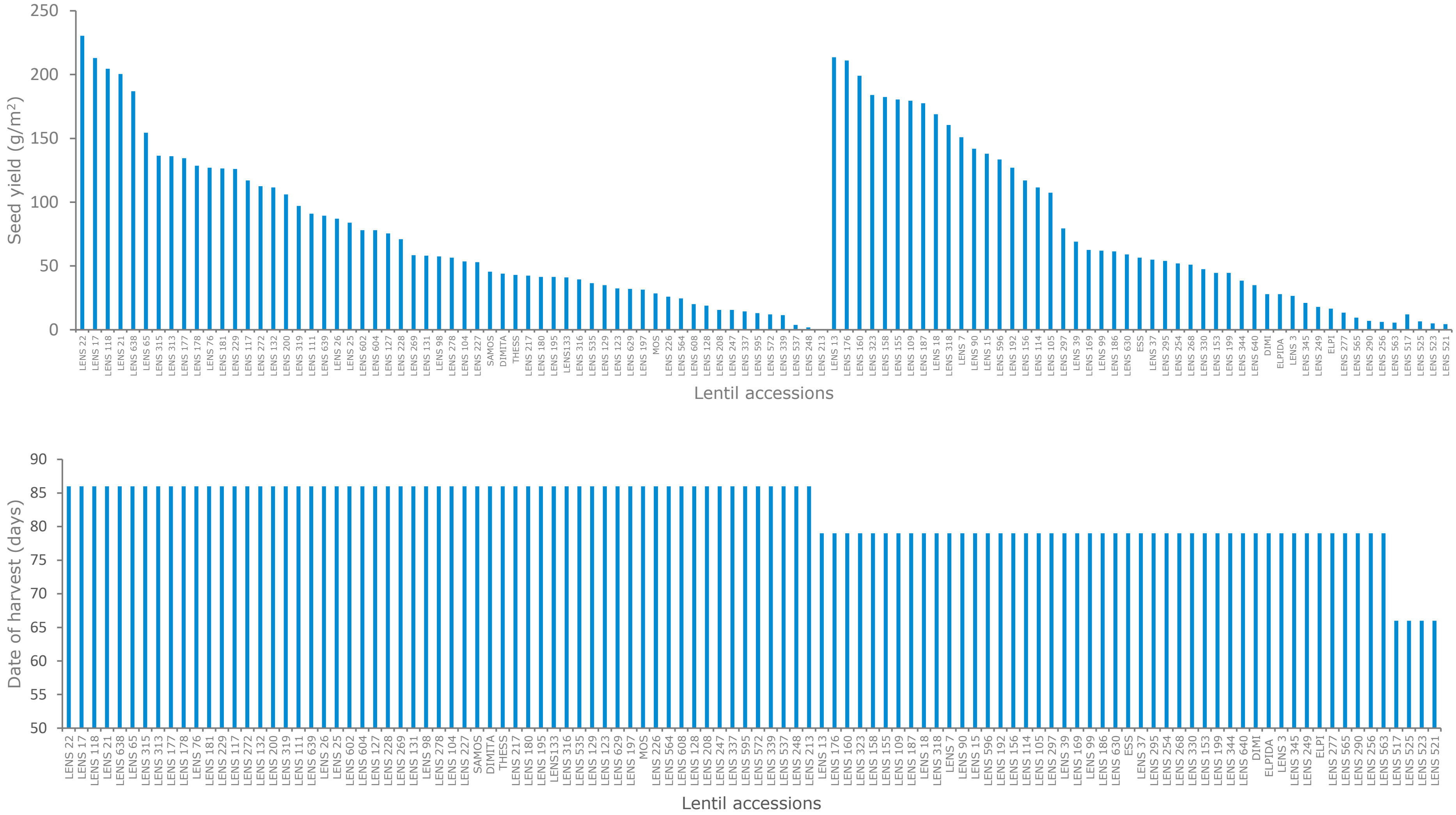


Figure 9. Date of harvesting (days from emergence) regarding to yield of accessions evaluated during 2023-24 cropping season in IPK.

Days to maturity among the lentil accessions ranged from 66 to 86 days, indicating substantial variability for this trait, which is closely associated with earliness and adaptation to hot and dry conditions. This pattern is consistent with observations for flowering time, highlighting the importance of phenological adaptation under stress-prone environments. The mean maturity was 82 days, only four days shorter than the maximum, suggesting that most accessions tended to mature relatively late under the experimental conditions.

The ultra early accessions (66 days) were generally characterised by low yield performance, indicating a trade-off between extreme earliness and productivity. In contrast, high-yielding accessions were distributed across the full maturity range, demonstrating that earliness and high yield can be combined. Notably, 15 superior accessions reached maturity three days earlier than the population average, representing valuable material for breeding programmes. Such early-maturing, high-yielding genotypes offer clear agronomic advantages, including reduced exposure to terminal drought and greater flexibility in harvest timing. Moreover, they are well suited to staggered mechanical harvesting, improving efficiency and management in large-scale production systems.

The cotyledons of the accessions under study showed two colour types: yellow (score 1) and orange/red (score 3) (

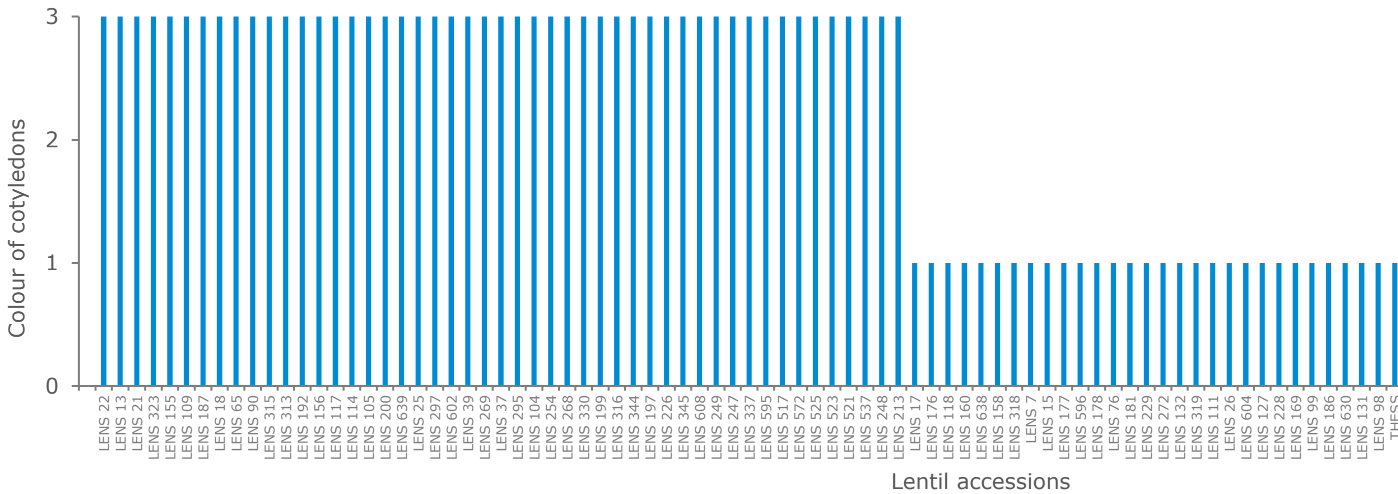


Figure 10).

Cotyledon colour is a basic qualitative trait, since it has a profound impact on consumer acceptability and regional market acceptability. Surprisingly, an equal number of high-yielding accessions, i.e., those that were well adapted and had good agronomic performance, were present in both colour types. This outcome suggests the presence of valuable genetic material for the achievement of two distinct breeding programmes based on orange/red cotyledons or yellow cotyledons. The presence of productive accessions in both colour classes supports that cotyledon colour will not negatively impact yield potential during lentil development. On the other hand, this diversity offers a strategic advantage, wherein breeders can design varieties for various markets without loss of agronomic performance. Cotyledon colour can be used as a selection trait in conjunction with yield for the production of market-oriented varieties that meet both productivity and preference needs in the future.

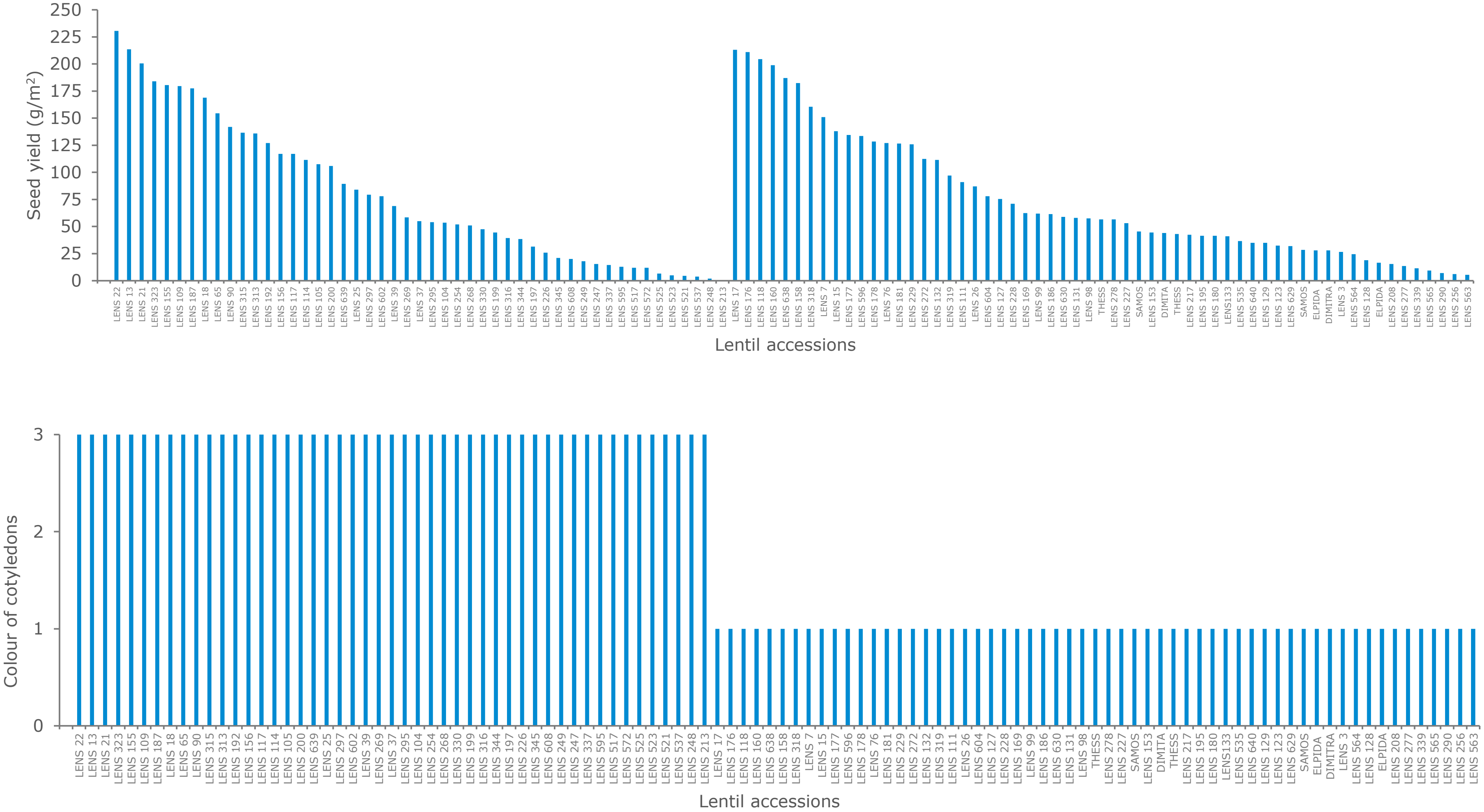
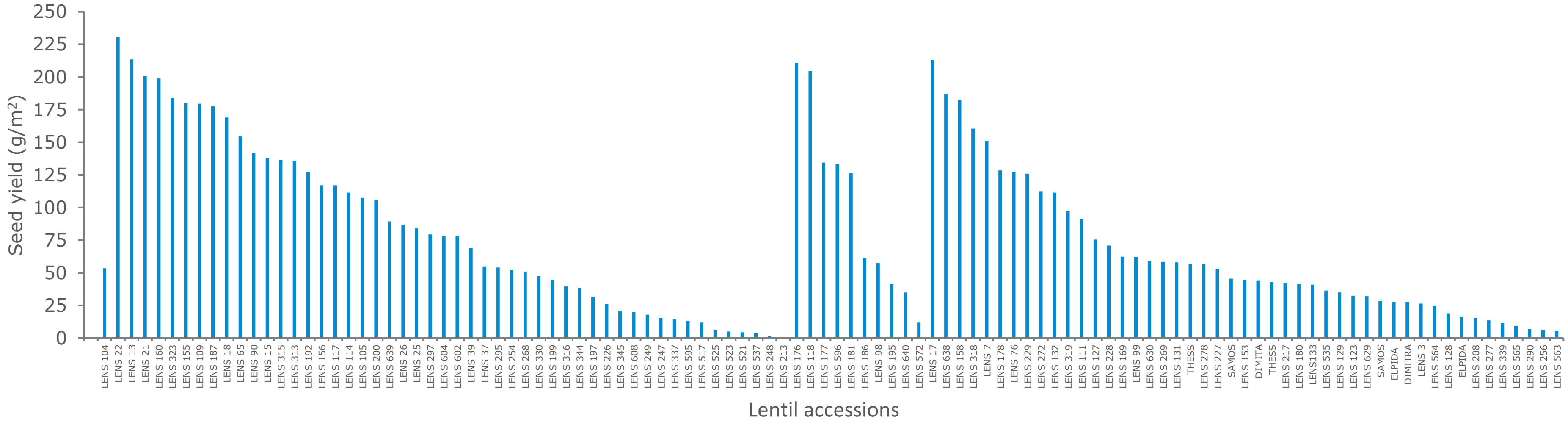


Figure 10 Colour of cotyledons (1=yellow, 3=orange to red) regarding the yield of accessions evaluated during 2023-24 cropping season in IPK.

Similar to the cotyledon colour trait, the colour of the testa (seed coat) is also a key qualitative characteristic in lentil and has a significant influence on consumer acceptance and marketability (Figure 11). Testa color is closely linked to regional culinary traditions and consumer preferences, making it a relevant selection trait in breeding programmes. Remarkably, a similar number of high-yielding accessions (those exhibiting strong adaptability and agronomic performance) were identified across all testa color categories, with the exception of black-coloured seeds. This indicates that there is substantial genetic potential available to support at least two distinct breeding programmes focused on different testa colors. Importantly, those data reveal that testa colour does not incur a yield penalty in most lentil accessions. However, black testa accessions had a significantly lower mean yield than the overall genotype mean revealing a specific challenge within this group. This suggests a requirement for a targeted improvement programme to enhance the productivity of black testa lentils, a valuable but underperforming resource currently. Developing high-yielding black testa lines would fill a niche market and enhance the flexibility of lentil varieties to meet both agronomic requirements and consumer preferences.



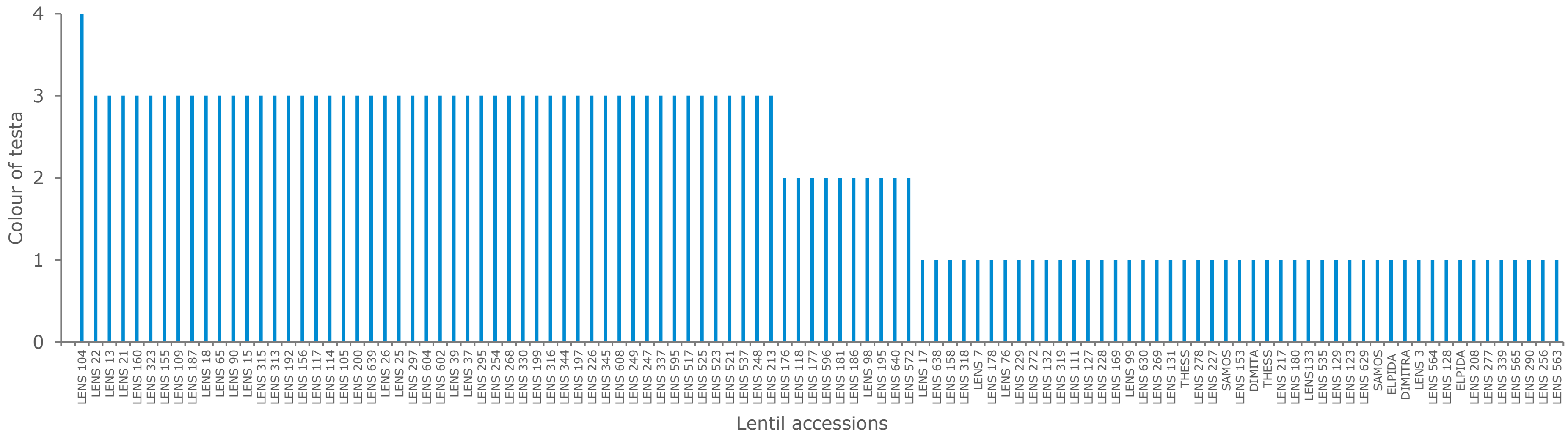


Figure 11. Colour of testa (1=green yelllow, 2=green, 3=pink, 4=black) and yield of accessions evaluated during 2023-24 cropping season in IPK.

The range of seed weight (TKW – thousand kernel weight) among the evaluated lentil accessions varied from 5 to 69 grams, indicating substantial genetic variability for this trait and suggesting significant potential for future improvement through breeding (Figure 12). Although seed weight is a component of yield, it did not show a direct correlation with overall productivity in this study. Accessions with the highest TKW values did not correspond to the highest-yielding entries. The most productive accessions were often characterized by medium or even low TKW values, indicating that yield performance is influenced more strongly by other components, such as seed number or plant architecture.

Most significantly, the greatest TKW values were found most frequently in accessions with yellow cotyledons, and this may reflect an interaction between seed color and seed size that could be explored further in subsequent research. These findings reflect the complexity of yield as a trait and support the importance of considering a number of components and their interactions when creating breeding schemes. Also, the possibility that some colour classes have high seed weight may offer opportunities for special improvement, depending on market or nutritional needs.

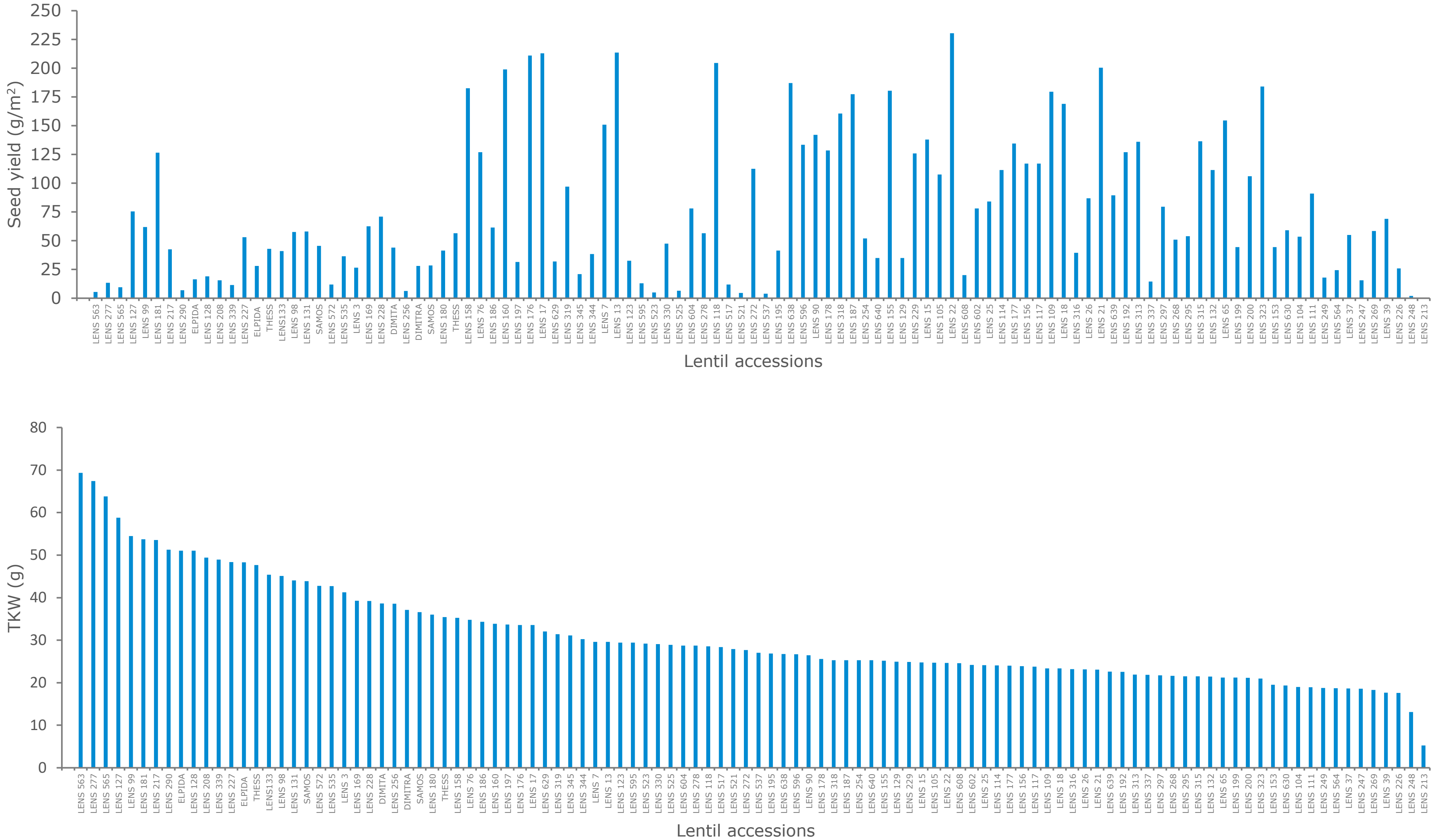


Figure 12. Seed yield (g/m²) and thousand kernel weight (TKW) of accessions evaluated during 2023-24 cropping season in IPK.

Cycle 2

During the field trials cycle 1, emphasis was placed on yield analysis and the identification of accessions exhibiting strong agronomic performance. Building on these results, cycle 2 of field evaluations was conducted, comprising 100 accessions tested in IPK, 100 tested in UNIBAS, 100 in Greece (tested in two locations), and 100 in KEY for validation purposes. This validation aimed to confirm the outcomes of the first cycle in relation to the agronomic performance of the tested accessions across Europe. A ranking of accessions was established based on yield performance, seed of local lentil varieties used as testers exchanged among France, Germany, Italy, and Greece in order to ensure the presence of common reference accessions across sites.

Crop yield is influenced by a combination of climatic parameters (temperature, rainfall distribution, drought, heat waves), soil conditions, and biotic stresses (pests and diseases), which can differ significantly between growing seasons and during the crop growing period. These factors contribute to strong genotype × environment (G×E) interactions, meaning that the relative performance and final productivity of accessions that can be potentially used as useful genetic resource is inconsistent across environments and years. As a result, the identification of truly productive genotypes or good accessions is challenging, since a genotype performing well in one season or location may not perform equally well under different conditions. This underlines the need for multi-environment and multi-year trials to assess both the general adaptability and the specific adaptability of accessions, thereby enabling a more reliable selection of promising starting material for breeding programmes.

The second cycle focused on validating first-cycle outcomes and provided the opportunity to examine both general adaptability (accessions performing well across sites) and specific adaptability (accessions performing well under local conditions). This approach ensured the reliability of the findings, enhanced cross-country comparability, and allowed the identification of accessions with strong productivity potential to be considered as starting material.

Trials were conducted across five locations—two in Greece, two in Germany, and one in Italy—covering a range of agro-ecological conditions. Commercial lentil varieties cultivated in France, Italy, Germany and Greece exchanged across the locations and included as checks. Plot sizes ranged from 0.5 to 3 m², and yield data were recorded on a per m² basis. Phenotypic evaluations followed a harmonised protocol agreed upon by the Lentil IC members, taking into account the CPVO/UPOV descriptor lists, consistent with the 1st cycle of evaluation (Table 1).

This approach enhanced the robustness and comparability of the results and facilitated the identification of high-performing accessions with strong potential as breeding material.

The cycle 2 field trials will support our focus on productive lentil accessions. In parallel with the field trials, a first attempt to use digital tools for phenotyping was made in Greece (IHU) to gain practical experience for the digital phenotyping of lentil accessions. Specifically, aerial imaging was conducted using a DJI Matrice 350 RTK drone equipped with a Micasense Altum PT multispectral camera. Image processing and analysis will be performed using Pix4D Fields software (Figure *13*) (. Given that phenotyping activities are conducted under field conditions, the aim was to explore common approaches and reference points for the integration of digital technologies into lentil phenotyping workflows. This activity is expected to provide a methodological basis for enhancing accuracy in trait measurement and reducing subjectivity in visual scoring. An overview of the field trials conducted during the period 2024-25 across Europe is presented below in the upcoming Figure 14, *Figure 15*, *Figure 16*, Figure 17, Figure 18 and Figure 19.

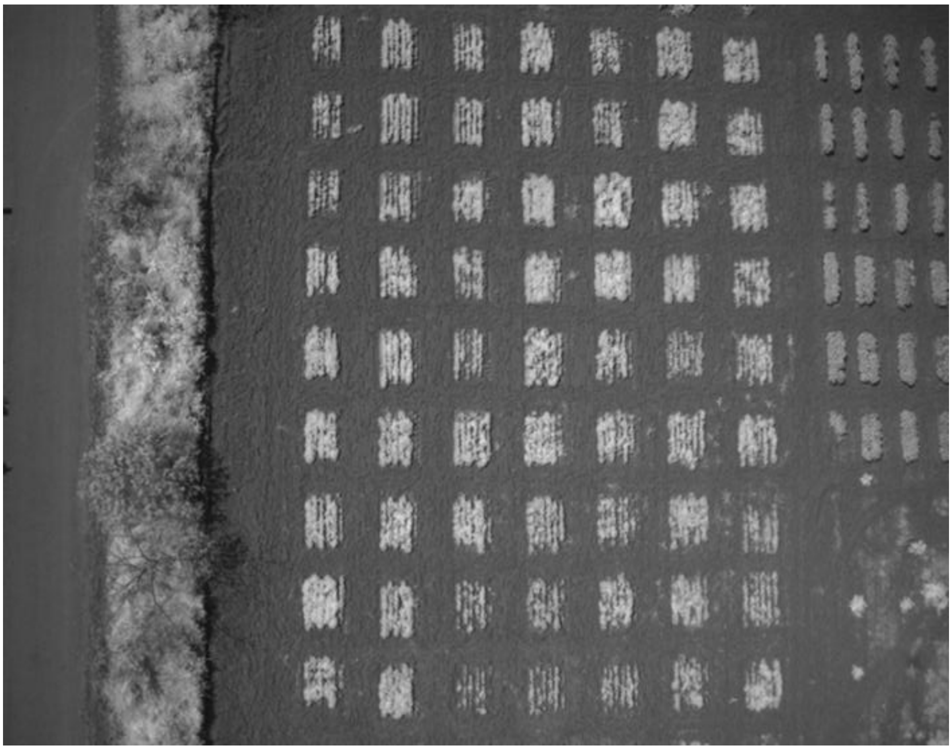


Figure 13. Aerial view of the lentil field trials, in IHU, Greece 2024-2025 (drone flight 23/04/2025, Sindos), Site 1.

Figure 14. A view of the lentil field trials at the IHU, Greece 2024-2025 (30/04/2025, Sindos, site1).

Figure 15. The lentil field trials to validate accession field performance, in IHU, Greece 2024-2025, (IHU, site 2).

Figure 16. Lentils accessions phenotyping in IPK, Germany 2024-2025.

Figure 17. Lentil accessions at different growth stages, IPK, Germany 2024-2025.

Figure 18. Lentil accessions under weed depression in KEY, during phenotyping, Germany 2024-2025.

Figure 19. Lentil accession phenotyping in UNIBAS, Italy 2024-2025.

The process enabled a robust validation of first-cycle results, strengthened by cross-country comparison and the inclusion of shared reference accessions. This provides a harmonised framework for subsequent cycles and supports the reliable identification of high-potential genetic material. The harvest was completed but the threshing and data collection is under process.

Lentil breeding methods and tools

The development and release of new lentil cultivars is a long-term process that often exceeds typical project durations. The Legumes Generation project builds on previous research to strengthen lentil breeding by systematically utilising existing germplasm resources, including landraces, accessions, and SSD lines.

The Lentil Innovation Community (Lentil IC) provides a collaborative platform across European regions, addressing the limited investment in lentil breeding by focusing on available genetic resources and different breeding methods applied from the field to the laboratory. Multi-location phenotypic evaluation within the same cropping season enables the generation of comparable data on adaptation and productivity.

The resources used included: (i) information of SSD lines performance developed in previous projects, (ii) evaluation data of accessions under diverse agro-climatic conditions, and (iii) germplasm (mainly accessions and/or SSD lines) previously developed or assessed. We used (1) the knowledge about the previously developed SSD lines to further work in crosses and the development of new breeding population and (2) the available germplasm resources or related information about these accessions to develop new SSD lines in the framework of the project and based on individual plant basis evaluation.

Work based on previous developed SSD lines

Focusing on the development of breeding populations and the application of modern selection tools, in the framework of the INCREASE project, UNIBAS developed SSD material and provided 11 SSD lines to UNIVPM for use in composite crosses. At UNIVPM, molecular diversity analyses based on PCA of approximately 450 SSD lines were performed to define suitable parental combinations. Composite crosses attempted in 2024 were unsuccessful due to high temperatures during the crossing period. However, successful selfing of nine selected genotypes ensured the availability of parental material for renewed crossing attempts in 2025.

UNIBAS has participated in the establishment of the list of parental lines to be used for the composite cross, providing seeds of the SSD lines of lentil coming from INCREASE project. Eleven lines have been selected according to phenotyping and genetic data. UNIBAS, responsible for the development of SSD lines within the INCREASE project, has sent the seeds materials to UNIVPM, in order to proceed with the respective crosses (Table 2).

Table 2. List of lentil SSD lines selected for the composite cross experiment.

Accession/ line code	IncreaseID
IG 1959	INLEN_00382
ILL 4605	INLEN_00411
PI 297767	INLEN_00502
PI 431663	INLEN_00583
PI 431710	INLEN_00587
PI 431753	INLEN_00593
PI 432033	INLEN_00608
PI 432245	INLEN_00620
PI 612875	INLEN_00650
Anicia	INLEN_01664
W6 27760	INLEN_00655

Results - Development of composite crosses (work from UNIVPM)
In the framework of Legumes Generation project, UNIVPM selected the parental lines to develop a composite cross of lentil. The molecular data available from the INCREASE project were used to investigate the molecular diversity of the INCREASE panel.

Over ~450 SSD accessions that are part of the INCREASE T-core panel have been included, and UNIVPM identified a set of lines, that, combining molecular data and our phenotypic data, maximize the diversity and can be suitable to be chosen for performing F1 crosses. A PCA using molecular data is provided in Figure 20. Accessions highlighted in the image are those we have finally selected to perform crosses in early 2024.

In addition to molecular data, we considered other available information such as productivity, protein content (high versus low protein content), flowering time and seed weight for the selection.

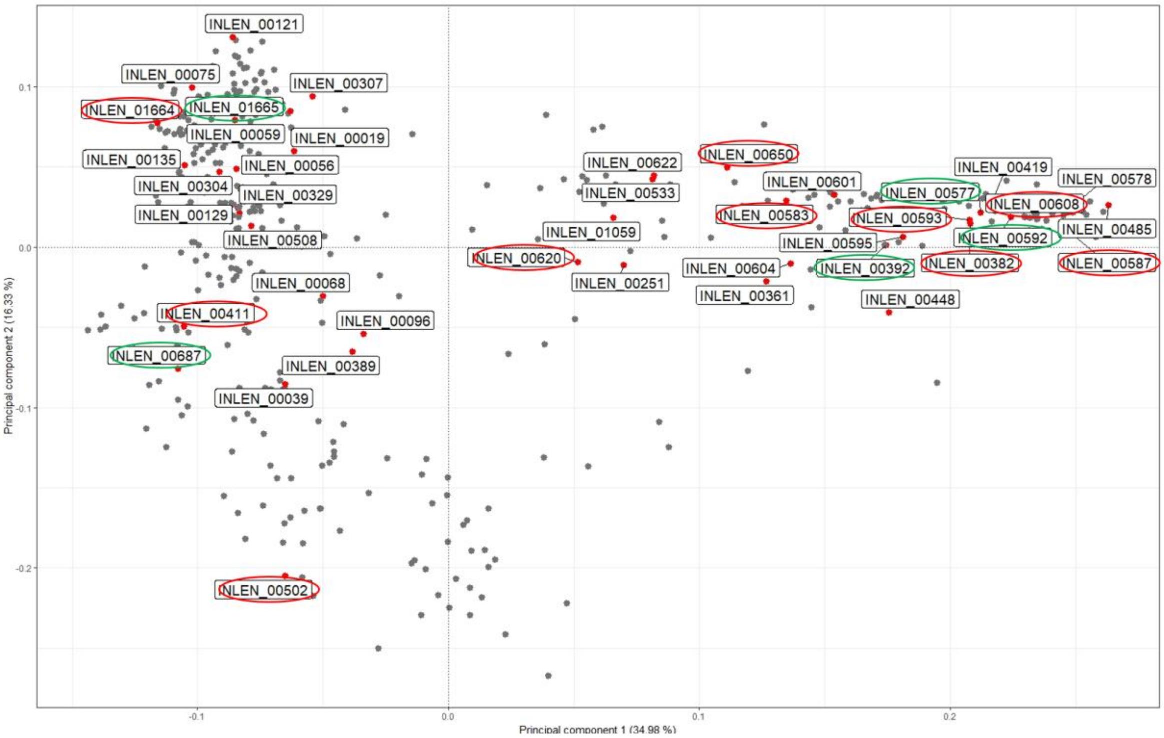


Figure 20. PCA analysis on SSD lines analysed by UNIVPM to develop composite crosses.

In the spring/summer 2024 UNIVPM performed sowing and carried out crosses under greenhouse conditions; however, these were unsuccessful probably due to the higher temperatures we have experienced. Despite this, seed multiplication was accomplished for a set of nine genotypes, where crossing failed but selfing succeeded, that will be used for the crosses in 2025 due to their better growth and tolerance. UNIVPM plans to repeat the cross in the 2025, by anticipating the sowing because the numbers of the seeds received is very low.

In parallel, since the beginning of the Legumes Generation project, IHU and Keyserlingk initiated single-plant selection under ultra-low-density field conditions, allowing the identification of highly productive individual plants (>10 g per plant), which are being advanced through SSD to form new breeding lines. IPK contributed genetic resources and technical expertise, while LIDEA provided guidance regarding traits of industrial relevance.

IHU used as a basis the information of the accessions that performed well in the Linsel project, and in combination of the methodology applied in the we evaluated on a field on individual plant basis.to produce monogenotypic lines (single seed descent) based on individual plant performance (Figure 21) information from Linsel project for best performing IPK accession, we investigate the productivity potential within available accessions on an individual plant basis. This identifies promising genotypes within the available lentil's germplasm from IPK. In collaboration with KEY and IPK, since the 1st year of the project (2023-2024) we had indication of accessions with possible good yield performance in North Europe (Linsel project).

Developing single plant selection within good performing accessions

Based on the phenotypic evaluation in T4.2, emphasis was placed on yield analysis and the identification of accessions exhibiting high agronomic performance. Building on these results, a second cycle of field evaluations was conducted, as described above, comprising 100 accessions tested at IPK, 100 at UNIBAS, 100 in Greece (across two locations), and 100 at KEY for validation purposes. This validation aimed to confirm the outcomes of the first cycle with respect to the agronomic performance of the tested accessions across Europe.

A ranking of accessions was established based on yield performance, and seed of local lentil varieties used as testers that exchanged among France, Germany, Italy, and Greece to ensure the presence of common reference accessions across sites. In addition, analyses were carried out to assess both specific and general adaptability of the accessions, based on yield performance across environments. This allowed the identification of accessions with consistently high performance as well as those with strong local adaptation. These results provide a solid foundation for selecting promising accessions to be used as starting materials with stability and good performance, this will serve as a genetic resources for new SSD lines production.

Figure 21. Testing yield performance on individual plant basis to produce SSD lines under low density and nil competition.

Productive SSD lines based on individual plant performance on the field in Legumes generation

We use as a basis the information of the accessions that performed well in the Linsel project, and in combination of the methodology applied in the we evaluated on a field on individual plant basis to produce monogenotypic lines (single seed descent) based on individual plant performance (**Fehler! Verweisquelle konnte nicht gefunden werden.**) information from Linsel project for best performing IPK accession, we investigate the productivity potential within available accessions on an individual plant basis. This identifies promising genotypes within the available lentil's germplasm from IPK. In collaboration with KEY and IPK, since year 1 of the project (2023-2024) we had indication of accessions with possible good yield performance in North Europe (Linsel project).

Lentil is an autogamous species with a high level of homozygosity; with the 1st year of legumes generation, we identified 10 individual plants with yield greater than 10 g / plant (Figure 22), these is from one seed – one plant. In Figure 21 shows the productivity distribution of individual plants within 20 different accessions that performed well in North Europe (year 2023-2024).

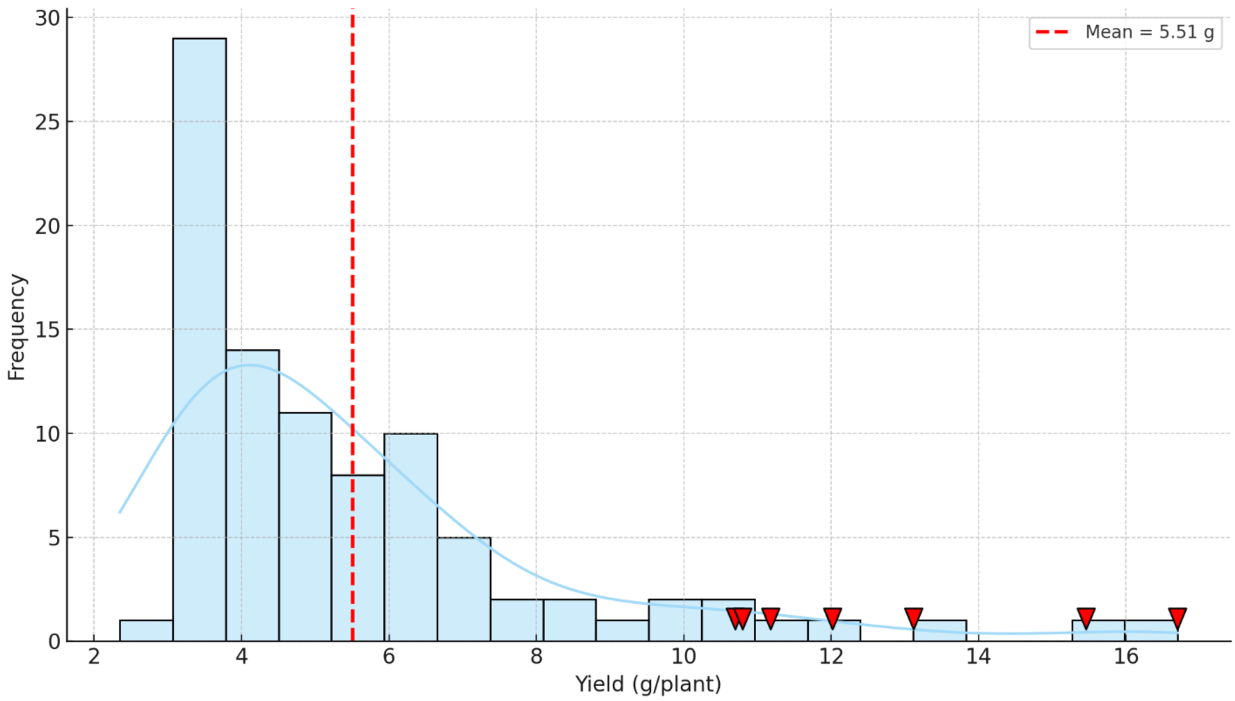


Figure 22. The productivity distribution of individual plants within 20 different accessions that performed well in northern Europe (IPK accessions performed well in Linsel project).

The distribution of the yield with mean revealed high yielding (>10 gr/plant) individual plants grown under low density, under nil competition, during year 2023-2024 in Greece, IHU. The productivity distribution of the best selected plants showed a productivity of 10 g / plant, these are SSD lines, since derived from one seed and tested under field conditions in the xerothermic environment in Greece (IHU). The evaluation is ongoing for year 2024-2025 to confirm the productivity under field conditions.

Field testing and demonstration

To date, demonstration activities were initiated by Keyserlingk in Germany, where 53 varieties and breeding lines, including six commercial checks, were evaluated under field conditions. The trials also included intercropping experiments with *Camelina sativa* and the sowing of 35 accessions for the assessment of winter hardiness. A farmer field day was successfully organised on 30 June, supporting knowledge exchange and stakeholder engagement.

Other partners will expand demonstration activities in the near future. Keyserlingk led the demonstration trials, while IPK participated in connection with the field day activities. IHU, UNIVPM, and UNIBAS have had no field activities but maintained a preparatory role for the next phase, while SRU, ESKUSA, and LIDEA remained involved in planning and coordination for future implementation.

Conclusion

Overall, the Lentil IC completed successfully the work for the 1st period of the project and established a strong foundation for the development of improved lentil cultivars by generating harmonised phenotypic data, validated germplasm, and new breeding resources. Promising breeding material is demonstrating improved yield stability, and resilience to drought, heat, and cold, supporting more competitive and climate-resilient lentil production across Europe. By exploiting diverse genetic resources, and work on the development of SSD lines, and composite cross populations, the Lentil IC is working to boost the productivity of lentil cultivars adapted to different European environments and production systems, particularly organic and low-input agriculture. In parallel, training activities and public–private collaboration are strengthening breeding capacity and accelerating the translation of research outcomes into practice, contributing to a more resilient, sustainable, and market-oriented European lentil sector.

Future perspectives

- Validate the results obtained during the first year through multi-environment evaluation.
- Identify and advance superior SSD lines within the most productive breeding families for further selection.
- Evaluate the selected material under controlled and field conditions for heat and drought stress tolerance.
- Expand the European evaluation network by including additional environments, partners, and stakeholders to strengthen genotype validation and accelerate cultivar development.

Literature

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