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Research article

Influence of the breed and litter breed composition on the growth, survival, and health of rabbits

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ABSTRACT

The aim of this work was to investigate the effect of the breed and the litter breed composition on the growth, survival, and health of rabbits. Two genetic types were compared: purebred INRA 1777 (**INRA**) and crossbreed ¾ Fauve-de-Bourgogne × ¼ INRA 1777 (**Crossbreed**). To study the effect of the litter breed composition, two cross-fostering strategies were used for suckled rabbits at birth: within-genetic type and between-genetic type, where the dam raised kits of the same or different genetic types. Litter composition was maintained after weaning. A total of 1 670 growing rabbits were monitored from birth to weaning (at 35 days of age), and then 1 030 rabbits were monitored from weaning to 64 days of age. Four cohorts were raised from September 2019 to April 2020. Health was evaluated using visual health scores and white blood cell counts. Crossbred rabbits had a higher survival rate in the preweaning period (+14.9% points; $P < 0.001$), and a higher percentage of healthy individuals at 64 days of age (+13.9% points; $P < 0.001$) than purebred rabbits, even though the survival rate was equivalent (92%) between the two genetic types in the postweaning period. Crossbred rabbits were lighter than INRA rabbits (−128 g at 64 days of age; $P < 0.001$). The between-genetic type cross-fostering strategy had a positive effect on survival in the preweaning period (+4.6% points for INRA and +13.3% points for Crossbreed; $P < 0.001$) compared to the within-genetic type cross-fostering strategy. No lasting effects of the litter breed composition on postweaning survival or health were observed. Mixing kits of different genetic types within litters may be a strategy to improve the overall herd health and help reduce the use of antibiotics in rabbit farming.

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Implications

Rearing two genetic types together could improve the health performance of the herd. During the preweaning period, litters composed of two genetic types had a higher survival rate than single−breed litters. After weaning, the complementary performances of the genetic types (one growing faster and one being more resistant) allowed a balance between health and productivity, which could contribute to the reduction of antibiotic treatments. Further research is necessary to investigate such practices in more detail. Such insights will be valuable in optimising cross-fostering strategies in rabbit farming, contributing to improving animal health and reducing the risk of antibiotic resistance emergence.

Specifications table

Subject	Breeding and Genetics
Type of data	Table, Graph, Figure
How data were acquired	Weight data were acquired using stabilised scales (accuracy 5 g) (SWR08-10S Platform 310X275 Trolley, Balea, Saint Mathieu de Tréviers, France) linked to an automatic recording system (AGPA, Balea, Saint Mathieu de Tréviers, France) with Bluetooth connection. Visual health status and mortality were assessed by direct observation of the animals. White blood cell counts was obtained using a Melet Schloesing MS 9–5 Hematology Analyzer (Osny, France). Statistical analyses were performed with

(*continued on next page*)

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	R-software version 4.2.2 (https://www.r-project.org/).
Data format	Raw data and analysed data in.tab (for tables) format. Supplementary Tables and Figure are found in the repository in.odt (for text) and.tif (for images) format.
Parameters for data collection	Rabbits were reared indoors and housed in wire cages (W × L × H: 46 × 90 × 60 cm). Before weaning, litters were housed with their dams or foster mothers. After weaning, the rabbits were housed in groups of five to six animals per cage.
Description of data collection	The data were collected on suckling and growing rabbits assigned to two cross-fostering strategies. Live weight was collected using scales at three time points (35, 57, and 64 days of age). The visual health scores of each individual were recorded by visual appraisal at weighting. Three mL of blood was collected from the central ear artery using 5 mL EDTA tubes and analysed the same day with the haematology analyser.
Data source location	Institution: INRAE – GenPhySE Sheep and rabbit experimental facility (https://doi.org/10.17180/ftvh-x393) City/Town/Region: Auzeville-Tolosane / Occitanie Country: France
Data accessibility	Repository name: Recherche Data Gouv Data identification number: https://doi.org/10.57745/RPD4LG
Related research article	No research article is related to this article.

Introduction

Many advances have been made in rabbit farming, primarily aimed at enhancing productivity. These improvements encompass nutrition, living environments, genetics, hygiene, and prophylaxis. Nevertheless, antibiotics have been extensively used in intensive livestock farming to maintain animal health, with approximately 23 tonnes of antibiotics sold to the French rabbit sector in 2021 (Anses, 2022). However, the excessive use of antibiotics has been linked to the emergence of antibiotic resistance, posing a threat to the effectiveness of antibiotics in both animal and human treatments (Kirchhelle, 2018; Angot, 2021). Consequently, reducing pharmaceutical use by employing these products judiciously and exploring alternative solutions is vital to contribute to public health and mitigate the risk of antibiotic resistance emergence.

Since the 1990 s, the implementation of "all-in-all-out" and "single batch" production systems has contributed to a 10% reduction in postweaning rabbit mortality (Maertens, 2007). This management encourages good hygiene practices, complete building cleaning and disinfection before starting a new production cycle, and facilitates multiphase feeding strategies, effectively reducing the risks of the emergence and spread of infectious diseases. Additionally, feed restriction during the fattening phase has been shown to decrease enteric problems in rabbits (Boisot et al., 2003; Gidenne et al., 2012). Together, these environment- and nutrition-based strategies significantly contributed to reduce antibiotic usage in rabbit farming.

Our study is part of the quest for alternative solutions to antibiotics by helping to develop farming systems that rely less on them. Building on the findings of King and Lively (2012), who demonstrated that the genetic diversity of host populations can offer protection against disease or parasites, we hypothesise that increasing genetic diversity in rabbits may promote health without the need for antibiotics.

Therefore, we used two genetic types in our study: a purebred of the INRA 1777 line (hereafter **INRA**) and a crossbred of ¾ Fauve-de-Bourgogne and ¼ INRA 1777 (hereafter **Crossbreed**). The INRA 1777 is a line selected on litter size and weaning weight that has always been reared inside buildings under biosecurity measures (Garreau et al., 2015). The Fauve-de-Bourgogne is a patrimonial breed historically used in small-scale farming, reared in outdoor hutches and selected by farmers through mass selection. Our hypothesis was that crossbreed rabbits should be more robust and resistant to disease, due to the selection history of the Fauve-de-Bourgogne breed and the increased genetic diversity (more heterozygosity) resulting from crossbreeding.

In this sense, our first objective was to assess the health and growth performances of the two genetic types. The second objective was to disentangle the effect of the genetic type itself (i.e. one genetic type being more robust and resistant to disease than the other) from a group effect (i.e. the concept of herd immunity where the susceptible genetic type is indirectly protected by the presence of the resistant genetic type; Fine et al., 2011).

In our study, we focused on survival during the preweaning phase and on survival, health, and growth during the postweaning (fattening) phase. To disentangle the effect of the genetic type from the group effect, we compared groups (litters before weaning maintained after weaning) composed of one or two genetic types. These litters were obtained by using two cross-fostering strategies at birth: the "within-genetic type" and "between-genetic type" strategies, where the dam raised kits of the same or different genetic types (pure and crossbreed). The within- or between –genetic type litters were maintained after weaning.

Material and methods

Animals

A total of 1 670 rabbits were born and monitored. They were born between September 2019 and January 2020 from 89 females of two genetic types: purebred INRA-1777 (n = 45) and crossbreed ½ Fauve-de-Bourgogne × ½ INRA-1777 (n = 44). A total of four artificial inseminations, 42 days apart, were performed to obtain the rabbit kits. Purebred INRA-1777 females were inseminated with fresh semen from 22 INRA-1777 males. Crossbreed females were inseminated with fresh semen of 25 Fauve-de-Bourgogne males. Therefore, INRA-1777 kits were purebred, while Crossbreed kits were ¾ Fauve-de-Bourgogne and ¼ INRA. A total of 408, 510, 422 and 330 rabbits were born in cohorts 1–4, respectively.

Experimental design

Preweaning period

The day after birth, rabbit kits were individually identified with ear tags ("Baby-Simplex", Chevillot®, Albi, France). On the same day, two cross-fostering strategies were applied (see Fig. 1). At each birth cohort (corresponding to the parturitions 1–4), half of the same number of available viable litters were assigned to the between-genetic type cross-fostering strategy, respecting the average litter size at birth of each genetic type for a given cohort (see Supplementary Table S1 at https://doi.org/10.57745/RPD4LG). The remaining litters were assigned to the within-genetic type cross-fostering strategy, also respecting the average litter size at birth of each genetic type. Dams always kept part of their own kits: for the between-genetic type cross-fostering strategy, half of the litter was composed of the dam's own kits. For the within-genetic type cross-fostering strategy, the adoption rate was 16%, meaning that 84% of the litter was composed of the dam's biological kits. The cross-fostered kits were randomly selected. The combination of genetic types and cross-fostering strategies gave four experimental groups: INRA kits in the within-genetic type cross-fostering strategy (**IW**, n = 465), Crossbreed kits in the within-genetic type cross-fostering strategy (**CW**, n = 452), INRA kits in the between-genetic type cross-fostering strategy (**IB**, n = 402) and Crossbreed kits in the between-genetic type cross-fostering strategy (**CB**, n = 348).

Postweaning (fattening) period

Of the 1 670 rabbits born, 460 died or were culled before weaning at 35 days of age. At weaning, the remaining 1 210 rabbits were distributed as followed in the experimental groups: 293 IW, 337 CW, 274 IB, and 306 CB. Of these, 172 rabbits (77 in cohort 1 and 95 in cohort 2) were used in another study with a concern to take a similar number of rabbits for each sex and experimental group, with the same weight distribution as in the original group. They were excluded from our study for the postweaning period. Therefore, we only kept the information on 1 038 rabbits for the postweaning period: 242 IW, 295 CW, 239 IB, and 262 CB. These came from the cohorts 1–4, with 247, 374, 272, and 145 rabbit kits, respectively.

Living environment

Maternity period (before weaning)

Each female was individually housed in polyvalent wired cages (W × L × H: 46 × 90 × 60 cm) at the INRAE GenPhySE – Sheep and rabbit experimental facility (https://doi.org/10.17180/ftvh-x393). The cages were equipped with a feeder, a drinker, a plastic footrest mat and an untreated pine-wood stick to gnaw. A plastic nest box (W × L × H: 46 × 25 × 10 cm), filled with untreated woodchips, was placed in the front part of each cage 4 days before and 21 days after parturition. The cages were in a room with natural and artificial lights ensuring a constant photoperiod of 16 h of light and 8 h of darkness throughout the experiment. The room temperature was set to vary between 13 and 26 °C. Females followed a theoretical parturition interval of 42 days. Artificial inseminations (**AI**) were performed 11 days after each parturition (all performed on the same date). Nonpregnant females were maintained for the next AI date. A female emaciated (visual inspection) or showing signs of illness around the AI date was rejected for AI at that date. Weaning took place 35 days after birth. Females and kits before weaning received (*ad libitum*) a lactation diet containing 3 858 kcal of gross energy, 18% of CP, 30% of NDF, 17% of ADF and 5% of ADL per kg of DM. For half of the females, the wheat grain in the diet (representing 23% of inclusion in fresh matter) was replaced by a mixture of barley (5%), oats (8%), triticale (5%) and wheat grain (5%). The reproductive performances of the females were described in a previous publication (Savietto et al., 2021a). As the preliminary analyses show no influence of the diet on the performances of the females or kits, we did not consider the diet effect in the statistical models.

Fattening period (from weaning)

At weaning, at 35 days of age, rabbit kits were individually marked with ear tattoos and placed in a fattening room, with the same equipment as in the maternity building. Weaned rabbits of cohorts 1, 3 and 4 were reared in the same room, while rabbits of the cohort 2 were reared in another room. Therefore, rabbits from cohorts 3 and 4 were kept together in the same room for 8 days, before rabbits of cohort 3 left the farm. Rabbits were placed in groups of five. Litters comprising more than 5 kits were split into two or more cages. If the group size was below five kits, additional kits from the same experimental group were added to complete the group. If needed, litters of six kits were also allowed. The genetic diversity at the group level (i.e. IW, CW, IB, and CB) was maintained after weaning. The photoperiod was set to 10 h of light and 14 h of darkness, and the room temperature was set to vary from 15 and 25 °C. Growing rabbits received a commercial diet containing 3 570 kcal of gross energy, 15% of CP, 38% of NDF, 21% of ADF and 6% of ADL per kg of DM, following a restriction plan: 50 g per rabbit the weaning day, then 90 g per rabbit between 36 and 42 days, 110 g per rabbit between 43 and 49 days, 130 g per rabbit between 50 and 56 days and *ad libitum* from 57 days old. No antibiotic treatment was given.

Studied variables

Survival of rabbit kits before and after weaning, and visual health score

The survival of kits between birth and 64 days of age was monitored daily. The date for death or culling was recorded. After weaning, the reason of death or culling was also recorded. The reason of death or culling was recorded if the event occurred after 35 days of age (weaning age). Survival data are presented as

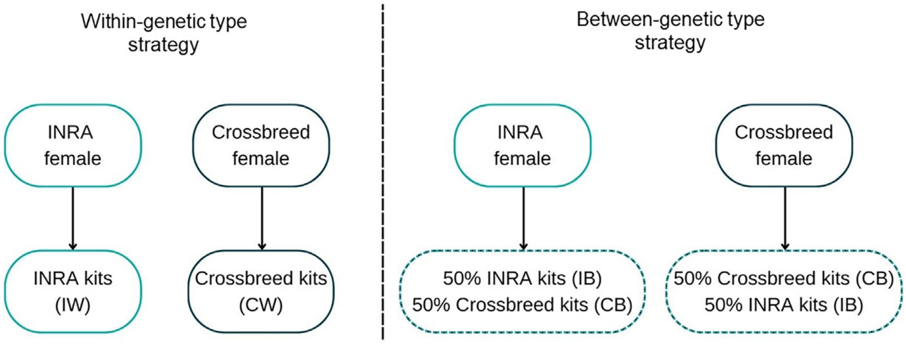

Fig. 1. Representation of cross-fostering strategies for rabbit females of each genetic type. **IW**: INRA kits in the within-genetic type cross-fostering strategy, **CW**: Crossbreed kits in the within-genetic type cross-fostering strategy, **IB:** INRA kits in the between-genetic type cross-fostering strategy and **CB**: Crossbreed kits in the between-genetic type cross-fostering strategy.

Kaplan-Meyer survival curves for the preweaning and the post-weaning periods. The maximum survival time was set to be 64 days of age, corresponding to the end of the experiment. There was no censored data. The health score of each animal was also assessed visually to record the clinical signs of disease at 64 days of age. A total of 952 rabbits were recorded and then classified as "healthy" or "sick".

Haematological traits

Between 64 and 67 days of age, 3 mL of blood was sampled from the central ear artery of a subgroup of 850 growing rabbits (197 rabbits for IW, 236 for CW, 199 for IB, and 218 for CB). The samples were analysed using the Haematology Analyser MS9-5 (Melet Schloesing Laboratoires, Osny, France) within 4 h after sampling to count the white blood cells (total white blood cells or **tWBC**, lymphocytes, monocytes, neutrophils and eosinophils). A representative subgroup of rabbits was sampled from each cross-fostering and genetic type combination at each birth cohort (see Supplementary Table S2 at https://doi.org/10.57745/RPD4LG). The density curves of white blood cell counts for each genetic type and cross-fostering strategy can be found in Supplementary Figure S1 at https://doi.org/10.57745/RPD4LG. The sampled subgroup included healthy and sick rabbits (See Supplementary Table S3).

Live weight and average daily gain

The live weight of each weaned rabbit was measured at ages 35, 57 and 64 days using a stabilised scale (5 g accuracy SWR08-10S Platform 310X275 Trolley, Balea, Saint Mathieu de Tréviers, France) linked to an automatic recording system (AGPA, Balea, Saint Mathieu de Tréviers, France) with Bluetooth connection (Laperruque and Staub, 2018). We also calculated the average daily gain (**ADG**) between 35 and 64 days of age, between 35 and 57 days of age, and between 57 and 64 days of age.

Statistical analysis

All statistical analyses were performed using the R statistical software version 4.2.2 (R Core Team, 2023). All traits were analysed at the animal level (with one measure per animal, unless stated otherwise).

Survival, visual health score, and mortality

A variable called Lifetime was set as the number of days between the birth or the weaning date and the date of death or culling (depending on the period analysed). The model used to produce the Kaplan-Meier estimation of survival probability curves included the growing rabbit's cross-fostering strategy (**CS**) and the rabbit genetic type (**G**). Log−rank test was performed to compare the survival curves. The model was implemented using the R-package {*survival*} (Therneau et al., 2023) as follows:

$$survfit(Surv(lifetime) \sim CS + G, Data\_frame)$$

For all the binary traits, visual health score (healthy: 0 or sick: 1) and mortality (alive: 0 or dead: 1), the data were analysed using a generalised linear model. We analysed the proportion of rabbits classified as 0 or 1 according to the cohort, the cross-fostering strategy, the genetic type and the interaction between CS and G.

The model in R-notation was:

$$glm(trait \sim cohort + CS * G, family = "binomial", Data\_frame)$$

Haematological traits

The blood cell counts (tWBC, lymphocytes, monocytes, neutrophils, eosinophils) were analysed under a linear model. The eosinophils were subjected to a square-root transformation to reduce the skewness of the distribution. The cohort, the cross-fostering strategy, the genetic type, and the interaction between CS and G entered the model as fixed effects. The model in R-notation was:

$$lm(blood\ \ cell\ \ count\ \ trait \sim cohort + CS * G, Data\_frame)$$

To evaluate if white blood cell counts could be an appropriate indicator of health, we studied their effects on the visual health score using a generalised mixed model.

The models in R-notation were as follows:

$$\begin{aligned} glm(Visual\ \ Health\ \ Score \sim cohort + CS * G + Lymphocytes \\ + Monocytes + Neutrophils \\ + sqrt(Eosinophils), family \\ = "binomial", Data\_frame) \end{aligned}$$

Live weight and average daily gain

The repeated measure of live weight from 35 to 64 days of age was analysed under a linear mixed model implemented using the R-package {*lme4*}. The cross-fostering strategy, the genetic type of the growing rabbit, the Age and their interactions entered the model as a fixed effect, and the Animal as a random effect. The model in R-notation was:

$$\begin{aligned} lmer(Live\_weight \sim\ cohort + CS * G * Age \\ + (1|Animal),\ Date\_frame) \end{aligned}$$

Live weight at each age (35, 57, and 64 days) and the corresponding ADG were also analysed under a linear model. The cohort, the cross-fostering strategy, the genetic type, and the interaction between CS and G entered the model as fixed effects. The model in R-notation was:

$$lm(weight\ \ trait \sim cohort + CS * G, Data\_frame)$$

Results

Preweaning survival

The overall mortality rate (death or culling) from birth to the day before weaning was 27.5%, with significant differences between genetic types (34.5% for INRA vs 19.6% for Crossbreed; $P < 0.001$) and cross-fostering strategies (31.3% for the within- vs 23.0% for the between-genetic type cross-fostering strategy; $P < 0.001$), but no significant interaction between them. The CB group had the lowest mortality (12.1%), whereas the mortality in the CW group was twice as high (25.4%). The highest mortality was found in the IB (32.4%) and IW (37.0%) groups.

The survival probability curve of INRA kits differed from that of Crossbreed kits ($P < 0.001$; Fig. 2A). The survival probability curve of the within-genetic type cross-fostering strategy differed from that of the between-genetic type cross-fostering strategy (Fig. 2B). The survival curves for the combination of genetic type and cross-fostering strategy were significantly different ($P < 0.001$; Fig. 2C), with CB survival curve differing from the other curves, and CW and IW curves differing from each other.

During the preweaning period, Crossbreed rabbits had a higher survival rate than the INRA rabbits. The cross-fostering strategy

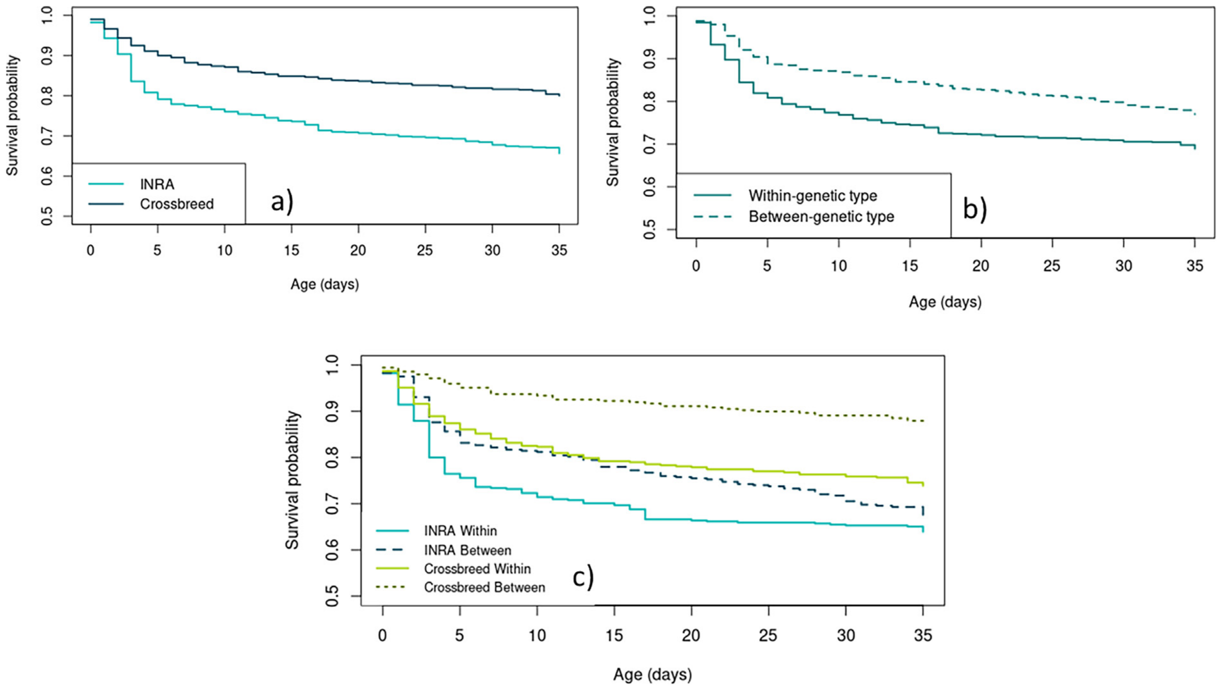

Fig. 2. Survival probability curves according to the rabbit genetic type or the cross-fostering strategy in the preweaning period. (a) Kit survival by genetic type: INRA or Crossbreed. (b) Kit survival by cross-fostering strategy: within- or between-genetic type. (c) Kit survival by genetic type and by cross-fostering strategy.

was beneficial for the survival of the young rabbits, regardless of their genetic type.

Postweaning survival

The overall mortality rate (death or culling) between weaning and 64 days of age was 7.8%, without any significant differences between genetic types or cross-fostering strategies. Within this period, the leading causes of death were digestive syndromes (66% of the cases) and respiratory syndromes (15% of the cases).

The survival probability curve of INRA kits differed from that of Crossbreed kits ($P < 0.001$; Fig. 3A). There was no significant difference between the two cross-fostering strategies (Fig. 3B). The survival curves for the combination of genetic type and cross-fostering strategy were statistically significant ($P < 0.001$; Fig. 3C). The Crossbreed survival probability curves (CB and CW) were significantly

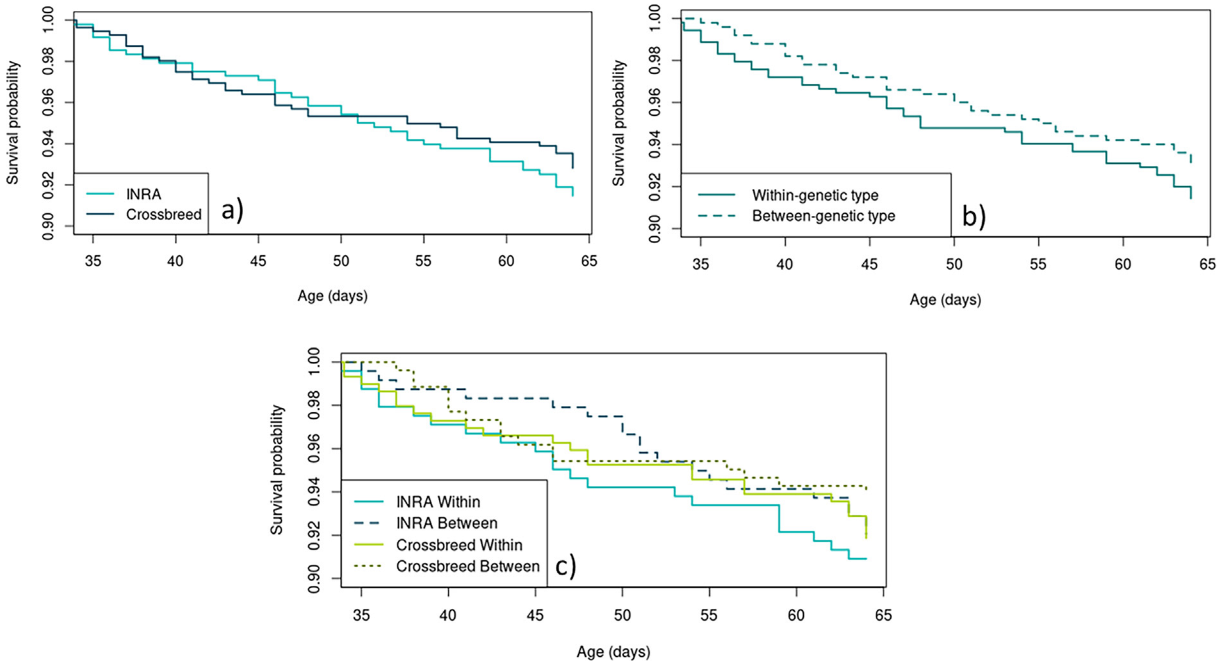

Fig. 3. Survival probability curves according to the rabbit genetic type or the cross-fostering strategy in the postweaning period. (a) Kit survival by genetic type: INRA or Crossbreed. (b) Kit survival by cross-fostering strategy: within- or between-genetic type. (c) Kit survival by genetic type and by cross-fostering strategy.

different from those of INRA (IW and IB; $P < 0.01$). The survival probability curves of Crossbreed (CB and CW) groups were identical throughout the growing period. Similarly, the survival probability curves of INRA (IB and IW) groups were identical throughout the growing period.

In contrast to the preweaning period, there was no effect of the cross-fostering strategy on survival, and the only difference between the genetic types concerned the shape of the survival curve and not the overall mortality.

Visual health score

The proportion of sick rabbits at 64 days old (Fig. 4) was significantly higher for INRA compared to Crossbreed rabbits (20.9 vs 7.0%, respectively; $P < 0.001$). There was no significant effect of the cross-fostering strategy and no significant interactions between the genetic type of the kits and the cross-fostering strategy. The diseased visual health score was related to respiratory syndromes for 89.1% of the sick rabbits and digestive syndromes for 7.8% of them, with no significant difference between the genetic type or cross-fostering strategy.

Haematological traits

The least–square means of the white blood cell populations according to the genetic type and cross-fostering strategy are shown in Table 1. For tWBC, monocytes, and neutrophils, an effect of the genetic type was observed, related to higher counts for INRA compared to Crossbreed (on average 8.39 vs 7.09 for tWBC; 0.70 vs 0.61 for monocytes; 4.87 vs 3.63 for neutrophils; $P < 0.001$). Overall, we did not observe an effect of the cross-fostering strategy or the interaction between genetic type and cross-fostering strategy for any white blood cell population.

In the sub-sample of rabbits with blood cell counts, we tested the effects of the cohort, genetic type, cross-fostering strategies and the different white blood cell populations on the visual health score using a generalised mixed model. Significant effects were found for cohort, genetic type, neutrophils (all with $P < 0.001$) and the lymphocytes ($P < 0.01$). Therefore, in our study, in which the sick rabbits presented mainly respiratory syndromes, neutrophils and lymphocytes were the most discriminating white blood cell populations between healthy and sick individuals.

The density curves of white blood cell counts according to the visual health score, the genetic type and cross-fostering strategies can also be found in Supplementary Figure S2 (see https://doi.org/10.57745/RPD4LG).

Live weight and average daily gain

Rabbit's live weight from 35 to 64 days of age is presented in Fig. 5 and Table 2. There was a significant effect of the genetic type ($P < 0.001$) on the repeated measure of live weight from 35 to 64 days of age, but no effect of the cross-fostering strategy or of the interaction between these factors. When weights were analysed separately at each age, the genetic type was always significant ($P < 0.001$) and there was a significant interaction between the genetic type and the cross–fostering strategy for live weight at 57 and 64 days of age ($P < 0.05$). The same pattern was observed for the ADG between weaning and 57, and between weaning and 64 days of age. INRA rabbits were always heavier than Crossbreed rabbits (+41 g at weaning, and +128 g at 64 days of age; $P < 0.001$). This corresponded to an ADG between 35 and 64 days of age of 38.4 g/day for INRA and 35.9 g/day for Crossbreed rabbits ($P < 0.001$). The significant interaction between genetic type and cross-fostering strategy appeared to be detrimental for the Crossbreed rabbits in the between-genetic type cross-fostering strategy as they tended to be lighter than when they were placed in the within-genetic type cross-fostering strategy.

Author's point of views

Comparison of the two genetic types

In our study, we compared two genetic types, INRA 1777 and crossbred rabbits ¾ Fauve-de-Bourgogne × ¼ INRA 1777. The INRA 1777 line is an experimental line selected for litter size at birth and weaning weight in a closed nucleus breeding system (with no introduction of reproducers from other breeds). Since the beginning of the selection, this line was raised in a protected building with appropriate biosecurity measures (Garreau et al., 2015). The

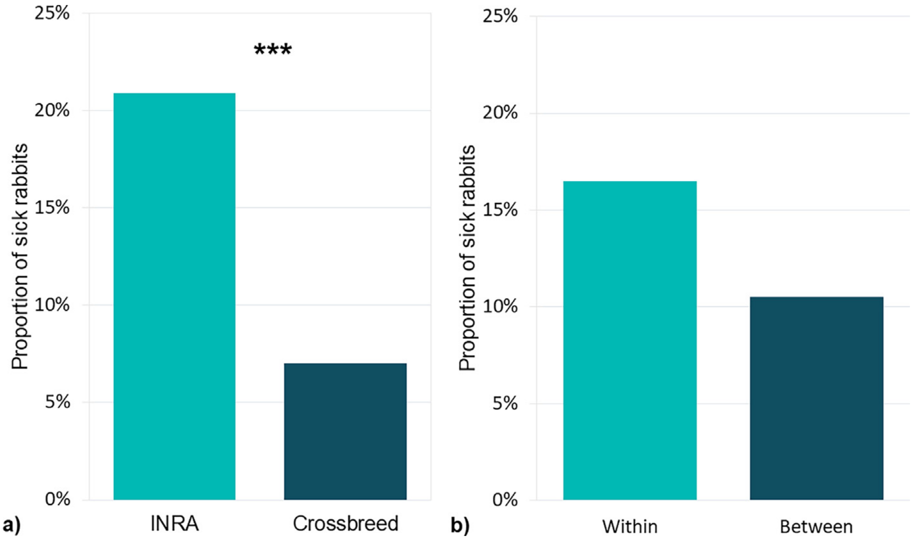

Fig. 4. Proportion of rabbits classified as sick at 64 days of age on the visual health score according to a) the genetic type (INRA or Crossbreed) or b) the cross-fostering strategy (within- or between-genetic type cross-fostering strategy), and P–value of these effects with ***~ $P < 0.001$.

Table 1
Least square means of the white blood cell counts (unit 10^3/mm^3) for each combination of rabbit genetic type (G: INRA or Crossbreed) and cross-fostering strategy (CS: within or between) and *P*-value of these effects.

Genetic type	INRA		Crossbreed		*P*-values (1)		
CS	Within	Between	Within	Between	G	CS	G × CS
tWBC (2)	8.40^{a}	8.38^{a}	7.14^{b}	7.04^{b}	<0.001	0.640	0.798
Lymphocytes	2.60	2.57	2.62	2.64	0.379	0.947	0.618
Monocytes	0.70^{a}	0.70^{a}	0.61^{b}	0.62^{b}	<0.001	0.368	0.564
Neutrophils	4.86^{a}	4.88^{a}	3.70^{b}	3.57^{b}	<0.001	0.557	0.465
Sqrt(Eos) (3)	0.22	0.23	0.26	0.23	0.306	0.070	0.057

(1) *P*-values of the main effects Genetic type (G), Cross-fostering Strategies (CS) and their interaction (G × CS).
(2) tWBC: total White Blood Cell counts.
(3) Sqrt(Eos): Square-root transformation of Eosinophils.
$^{a-b}$ Values having different superscripts differ at $P < 0.001$.

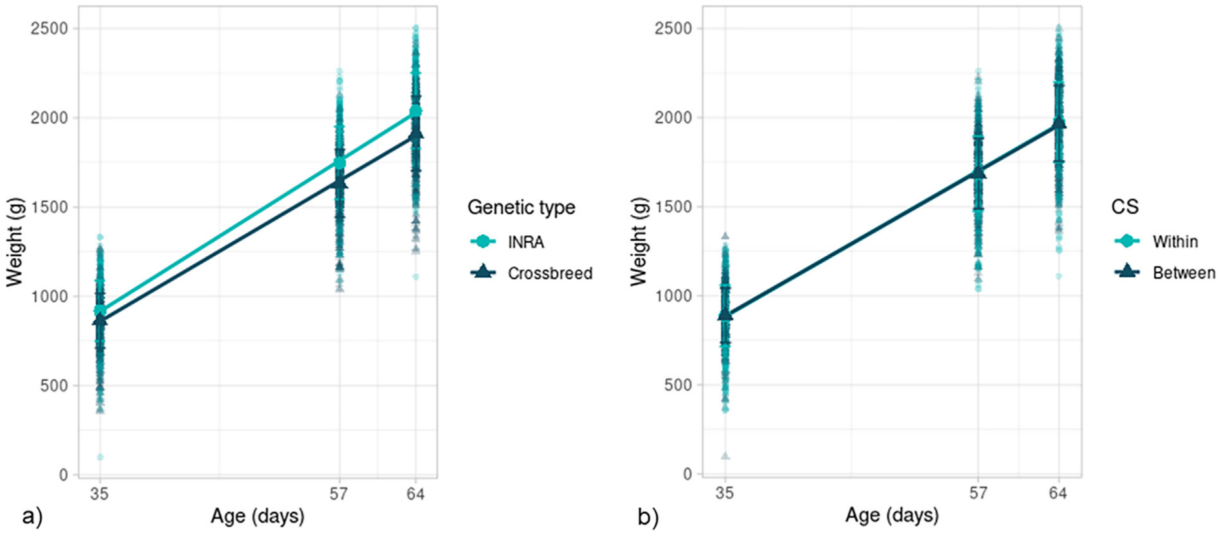

Fig. 5. Live weight (in grams) of growing rabbits between 35 and 64 days of age according to a) the genetic type (INRA or Crossbreed) or b) the cross-fostering strategy (CS: within- or between-genetic type cross-fostering strategy).

Table 2
Least square means of live weight and average daily gain (in grams) for each combination of rabbit genetic type (G: INRA or Crossbreed) and cross-fostering strategy (CS: within or between) and *P*-value of these effects.

Genetic type	INRA		Crossbreed		*P*-values (1)		
CS	Within	Between	Within	Between	G	CS	G × CS
LW35 (2)	916^{a}	922^{a}	875^{b}	874^{b}	<0.001	0.780	0.752
LW57	$1\ 726^{a}$	$1\ 758^{a}$	$1\ 656^{b}$	$1\ 631^{b}$	<0.001	0.969	0.017
LW64	$2\ 026^{a}$	$2\ 056^{a}$	$1\ 943^{b}$	$1\ 911^{b}$	<0.001	0.814	0.019
ADG35-57 (3)	37.4^{a}	38.2^{a}	35.7^{b}	34.8^{b}	<0.001	0.780	0.009
ADG57-64	43.3^{a}	43.2^{a}	41.2^{a}	41.1^{a}	0.003	0.784	0.918
ADG35-64	38.1^{a}	38.6^{a}	36.4^{b}	35.6^{b}	<0.001	0.447	0.022

(1) *P*-values of the main effects Genetic type (G), Cross-fostering Strategies (CS) and their interaction (G × CS).
(2) LW35, LW57, LW64: live weight at 35 days (weaning age), 57, and 64 days of age.
(3) ADG35-57, ADG57-64, ADG35-64: average daily gain for the corresponding age interval
$^{a-b}$ Values having different superscripts differ at $P < 0.05$.

Fauve-de-Bourgogne breed, on the contrary, is a patrimonial breed historically used in small-scale farming. Animals of this local breed have generally been raised in open or semi-open air in concrete (or wooden) hutches and the mass selection performed by local farmers maintained a reasonable prolificacy and growth rate (Bolet, 2002; Bolet et al., 2004). A previous study (Savietto et al., 2021b) showed that this breed could be interesting in a crossbreeding scheme with prolific lines such as INRA 1777. Our initial hypothesis was that Crossbreed would be more robust and resistant to disease. In fact, Crossbreed showed a significantly higher proportion of healthy visual health score at 64 days compared to INRA, and had a higher survival rate in the preweaning period than INRA. Two reasons could explain the better fitness of Crossbreed: a higher resistance and immune competence of the Fauve-de-Bourgogne breed, which is reared in harsher conditions and probably more exposed to disease than INRA rabbit reared in highly controlled conditions, and an increased level of heterozygosity with a favourable heterosis effect on health traits due to crossbreeding. Previous studies have shown that heterosis has a very positive effect on health (Blasco et al., 1993; Bunning et al., 2019). The two genetic types had different live weights, with INRA being heavier than Crossbreed, and different means for haematological traits.

Comparison of the two cross-fostering strategy

We increased the diversity at the litter level by using the between-genetic type cross-fostering strategy. Suckling kits of one genetic type were mixed with kits of the other genetic type when reared together by their foster mother. This mixture of genetic types was also maintained during the postweaning periods, with both genetic types being reared in the same cage (for the CB and IB groups). Our hypothesis was that both genetic types should benefit from a herd immunity effect, with the robust and resistant breed providing protection to the more susceptible one. Indeed, the between-genetic type cross-fostering was beneficial for INRA and Crossbreed during the preweaning period. It seems that the mixed litter (composed of the two genetic types) provided a favourable environment for all the kits in the litter. This protective effect of the between genetic type cross-fostering strategy disappeared in the postweaning period. After weaning, the cross-fostering strategy had no effect on survival, and no effect was observed on visual health scores and haematological traits. For growth traits, there appeared to be an unfavourable interaction between genetic type and cross-fostering strategy, with the lighter Crossbreed possibly suffering from competition for feed with INRA when they were reared in the same cages. As they were fed *ad libitum*, a behavioural analysis will be required to confirm this hypothesis. Cross-fostering within a genetic type is a common practice in pig and rabbit farming because there are too many piglets or kits born alive and the surplus from one litter is cross-fostered to create a new litter group (Maertens et al., 1988). This practice tends to increase preweaning survival (Heim et al., 2012), as the competition between litter mates for milk is balanced. However, no studies had been conducted in rabbits using cross-fostering between breeds, and the postweaning effect was unknown. The present results might interest rabbit farmers in keeping different breeds or having purebred and crossbred rabbits as cross-fostering between genetic types increases the survival before weaning. Further studies are needed to confirm our results with other genetic types. Cross-fostering between genetic types (strains) has been widely practised in laboratory rats and mice to study the effect of the postnatal environment (McCarty, 2017). In some cases, cross-fostering did not modify particular phenotypic traits (such as open-field behaviours or aggressive behaviours). In other cases, cross-fostering impacted the offspring of one strain but not the offspring of the other (such as freezing, cognitive behaviours, or some aggressive behaviours of some strains); or, like for the preweaning mortality in our study, cross-fostering modified the phenotypic characteristic (survival) in the offspring of both strains. In laboratory rodents, such effect on both strains was observed for maternal behaviour (McCarty, 2017): pups reared by their biological mother exposed to prenatal stress displayed aggressive maternal behaviour, in contrast to cross-fostered rats (stressed pups reared by control mother or control pups reared by stressed mother) which displayed normal maternal behaviour patterns.

Conclusion

We investigated the influence of the genetic type and cross-fostering strategy on rabbit health. Crossbreed rabbits showed a higher survival in the preweaning period, and better visual health scores at 64 days. The between-genetic type cross-fostering strategy was highly beneficial for the survival of both genetic types in the preweaning period. After weaning, this protective effect disappeared, and no effect on survival or health traits was observed. Keeping two genetic types in the same herd and applying a between−breed cross-fostering strategy may therefore improve the overall herd health and limit the use of antibiotics in rabbit production. The lower weight at selling age of the Crossbreed would be compensated by its better health and preweaning survival and by the benefit of the between-genetic type cross-fostering strategy on preweaning survival. Further research is needed to explore the full benefits of these practices at the herd level by comparing herds using two genetic types with purebred herds. In this aspect, some questions still need to be treated, such as: What is the optimal breed composition of litters to get some protective effect against diseases? Which combinations of breeds, in time and space, are required to improve the overall health of the herd?

Peer Review Summary

Peer Review Summary for this article (https://doi.org/10.1016/j.anopes.2024.100083) can be found at the foot of the online page, in Appendix A.

Ethics approval

The French Committee (number 115) for Ethics, Science and Animal Health approved all the experimental interventions on animals. The committee followed the provisions laid down in articles R.214-87 to R.214-126 of the French Rural Code and the French Ministry of High Education, Research and Innovation approved the study. The experiment permit number is 14950-2018042615284335.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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