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USO DE ÍNDICES DE EFICIENCIA ALIMENTICIA PARA INCREMENTAR LA PRODUCTIVIDAD EN OVINOS DE PELO

CARLOS ARCE RECINOS

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USO DE INDICES DE EFICIENCIA ALIMENTICIA PARA INCREMENTAR LA PRODUCTIVIDAD EN OVINOS DE PELO.

Carlos Arce Recinos, Dr.

Colegio de Postgraduados 2021.

Se evaluó la eficiencia alimenticia en treinta corderos Pelibuey no castrados, utilizando los índices consumo de alimento residual (CAR) y ganancia e ingesta residual (GIR). Los corderos fueron alimentados durante 92 días y luego sacrificados, con el objetivo de identificar la relación entre los índices de eficiencia alimenticia y el comportamiento productivo, parámetros de fermentación ruminal, características de la canal, rasgos de calidad de la carne, tamaño de órganos distintos a la canal y depósitos de grasa interna. Los valores medios de las clases fueron -0,09, 0,00 y 0,09 kg MS/d para bajo, medio y alto CAR. Las medias de GIR fueron 2.6, -0.1 y -2.7, para alta, media y baja, respectivamente. Los corderos con bajo-CAR mostraron una menor ingesta de alimento sin comprometer la tasa de ganancia diaria. Los corderos con alta-GIR mostraron una ganancia diaria promedio más alta y una mejor conversión alimenticia ($P \leq 0.05$). Los corderos con bajo-CAR y alta-GIR tuvieron valores más altos ($P < 0.05$) para pérdida por cocción en la carne y peso del corazón. Se encontraron diferencias ($P < 0.01$) hacia mayor volumen de sangre y menor peso relativo en los depósitos de grasa omental y total en corderos con bajo-CAR. Los corderos eficientes tienen un corazón más grande, lo que podría estar relacionado con un rendimiento cardiovascular mejorado y mayor eficiencia alimenticia, sin afectar los parámetros fermentativos ruminales, rasgos de la canal y la calidad de la carne (excepto por la pérdida de cocción).

Palabras clave: consumo de alimento residual, ganancia e ingesta residual, corderos.

USE OF FEED EFFICIENCY INDICES TO INCREASE PRODUCTIVITY IN HAIR SHEEP.

Carlos Arce Recinos, Dr.

Colegio de Postgraduados 2021.

Feed efficiency was evaluated in thirty uncastrated Pelibuey lambs, using the residual feed intake (RFI) and residual intake and gain (RIG) indexes. The lambs were fed for 92 days and then slaughtered, with the objective of identifying the relationship between feed efficiency indices and productive behavior, rumen fermentation parameters, carcass characteristics, meat quality traits, size of non-carcass organs and internal fat deposits. The mean values of the classes were -0.09, 0.00 and 0.09 kg DM/d for low, medium and high RFI. The means of RIG were 2.6, -0.1 and -2.7, for high, medium and low, respectively. Lambs with low-RFI showed lower feed intake without compromising daily rate of gain. Lambs with high-RIG showed higher average daily gain and improved feed conversion ($P \leq 0.05$). Lambs with low-RFI and high-RIG had higher values ($P < 0.05$) for cooking loss in meat and heart weight. Differences ($P < 0.01$) were found toward higher blood volume and lower relative weight in omental and total fat deposits in low-RFI lambs. Efficient lambs had a larger heart, which could be related to improved cardiovascular performance and higher feed efficiency, without affecting ruminal fermentative parameters, carcass traits and meat quality (except for cooking loss).

Key words: residual feed intake, residual intake and gain, lambs.

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INTRODUCCIÓN GENERAL.

El consumo de alimento es uno de los factores más importantes en los sistemas intensivos de producción de carne ovina, y representa más del 70% de los costos totales de producción (Lima *et al*., 2017). Por ello, la selección de animales eficientes en la utilización del alimento, que presenten una menor ingesta de alimento, manteniendo su rendimiento o incrementando la producción con una ingesta similar, podría incrementar la rentabilidad de los sistemas (Ellison *et al*., 2017). Esto es importante, debido a que la reducción de los costos de alimentación contribuiría a mantener los precios rentables dentro de un mercado de insumos agrícolas fluctuantes y la competitividad en el mercado global.

El consumo de alimento residual (CAR o RFI "residual feed intake" por sus siglas en inglés) y la ganancia e ingesta residual (GIR o RIG "residual intake and gain" por sus siglas en inglés) son dos índices de eficiencia alimenticia (IEA), que se han popularizado en las últimas décadas debido a que son independientes del tamaño corporal y el nivel productivo (Berry & Cowley, 2012). El CAR permite identificar a los animales más eficientes en la utilización de los alimentos y, mediante programas de cría lograr una mejora genética del hato ganadero, además, de reducir los costos de la producción de cada kilogramo de peso vivo incrementado (Arthur & Herd, 2008). El GIR permite seleccionar animales que presentan mayor ganancia diaria de peso (GDP) y menor consumo de materia seca (CMS), debido a que el GIR se correlaciona negativamente con el CMS y positivamente con la GDP (Berry & Cowley, 2012).

Recientemente, se ha reportado en ovinos que los animales eficientes (bajo-CAR) presentan una tasa de crecimiento similar a los ineficientes, sin embargo, se ha observado un menor CMS, registrándose diferencias de 160-190 g/d entre ambos grupos (Lima *et al*., 2017; Zhang *et al*., 2017; Montelli *et al*., 2019). Cuando se usa el índice GIR, la tasa de conversión alimenticia en corderos eficientes (alta-GIR) disminuye en un rango de 16 a 22% comparado con animales ineficientes (Lima *et al*., 2017; Carneiro *et al*., 2019, Nascimento *et al*., 2020). Esto se debe, a que los animales eficientes tienen un menor requerimiento de energía para el mantenimiento (Castro-Bulle *et al*., 2007; Gomes *et al*., 2012). Además, estos IEA no tienen un efecto negativo sobre las características (peso, rendimiento, espesor de grasa subcutánea, profundidad, amplitud y área del músculo *longissimus dorsii*) de la canal (Carneiro *et al*., 2019; Nascimento *et al*., 2020), ni de la calidad (pH, color, capacidad de retención de agua, fuerza al corte) de la carne (Montelli *et al*., 2021). Mientras que, se ha informado que los corderos eficientes (bajo-CAR y alta-GIR) tienden a depositar una menor cantidad de grasa visceral (Carneiro *et al*., 2019; Montelli *et al*., 2021) y presentan un hígado de menor peso relativo (Zhang *et al*., 2017).

Por otro lado, se ha informado que la concentración de ácidos grasos volátiles (AGV) en el rumen de corderos clasificados como bajo-CAR y alimentados con una dieta concentrada, tienen mayor proporción de propionato (Ellison *et al*., 2017; Liang *et al*., 2017), lo que sugiere que el microbioma del rumen de corderos eficientes alberga especies microbianas especializadas en la producción de propionato que desempeñan un papel importante en el aumento de la eficiencia alimenticia (Ellison *et al*., 2017). Un estudio reciente indicó que el rumen de los corderos eficientes alberga comunidades microbianas más abundantes y diversas en comparación con los corderos ineficientes, y tienen una relación *Firmicutes*: *Bacteroidetes* más alta, que está relacionada con el metabolismo energético (Zhang *et al*., 2021). Además, se ha informado que el ganado eficiente tiene un epitelio ruminal más grueso, lo que sugiere un aumento de la actividad metabólica y funcional del epitelio (Lam *et al*., 2018).

En México, la producción ovina es una de las actividades pecuarias con mayor presencia en su distribución territorial; las cifras preliminares del 2018 indican que la población ovina alcanzó un total de 8.7 millones de cabezas (SIAP, 2020), siendo la raza Pelibuey una de las más numerosas, ya que es utilizada como pie de cría por su habilidad materna, alta prolificidad, rusticidad, resistencia a parásitos y su gran adaptación a las diversas condiciones climáticas presentes en el país, para la producción cárnica (Chay-Canul *et al*., 2016). Sin embargo, se tiene poca información acerca de la selección genética de ovinos haciendo uso de los IEA; en este sentido es importante generar datos que ayuden a seleccionar ovinos más eficientes con el objetivo de reducir los costos de producción de la explotación ovina y adicionalmente utilizar los IEA como una herramienta que puede ser incluida en los índices de selección para mejorar el mérito genético. Por lo que, es necesario evaluar las relaciones de estos IEA con el comportamiento productivo, características de la canal y calidad de carne, parámetros fermentativos ruminales y el tamaño de órganos viscerales en ovinos Pelibuey.

OBJETIVOS.

Objetivo general

Evaluar la relación de los índices de eficiencia alimenticia CAR y GIR sobre la productividad y calidad de la carne de ovinos Pelibuey en condiciones del trópico húmedo de México.

Objetivos específicos

- ✓ Evaluar el efecto del CAR y GIR en la ganancia diaria de peso e ingesta de materia seca en ovinos de pelo.
- ✓ Evaluar la composición química de la dieta y alimento rechazado, para determinar el consumo de materia seca, consumo de materia orgánica, consumo de proteína, y el consumo de fibra detergente neutro.
- ✓ Evaluar la concentración de ácidos grasos volátiles en ovinos Pelibuey con diferentes clases de CAR y GIR.
- ✓ Evaluar las características y calidad de la canal en ovinos de pelo con diferentes clases de CAR y GIR.
- ✓ Evaluar el tamaño de los órganos viscerales, tracto gastrointestinal, deposición de grasa y componentes de desecho en ovinos de pelo con diferentes clases de CAR y GIR.

HIPOTESIS.

I. Los indicadores de eficiencia alimenticia CAR y GIR, permitirán identificar corderos eficientes en el uso del alimento.

II. Los corderos eficientes (CAR bajo y GIR alto) en el uso de los compuestos de la ración tendrán una menor tasa de crecimiento en relación con los animales ineficientes.

III. Los corderos eficientes (CAR bajo y GIR alto) en el uso de los compuestos de la ración tendrán una menor concentración de ácido propiónico en relación con los animales ineficientes.

IV. Los corderos eficientes (CAR bajo y GIR alto) presentarán una menor calidad de la canal y calidad de carne en relación a los animales ineficientes.

V. Los corderos eficientes (CAR bajo y GIR alto) tendrán un menor tamaño de órganos viscerales y menor deposición de grasa corporal en relación a los animales ineficientes.

CAPÍTULO 1. ÍNDICES DE EFICIENCIA ALIMENTICIA EN OVINOS DE PELO: CALIDAD DE LA CARNE Y GENES ASOCIADOS: REVISIÓN.

Resumen.

Los ovinos de pelo desempeñan un papel importante en la producción de carne en las zonas tropicales, donde los estudios de eficiencia alimenticia han sido poco evaluados. El consumo de alimento representa más del 70% de los costos de producción; por lo tanto, la selección de animales con alta eficiencia alimenticia puede mejorar la rentabilidad del sistema de producción. Se han desarrollado herramientas que permiten seleccionar individuos con mayor eficiencia alimenticia sin comprometer la calidad del producto. Por lo que esta revisión tiene la finalidad de identificar estas herramientas genético-moleculares y estadísticas, como son, el consumo de alimento residual (CAR) y ganancia e ingesta residual (GIR). En la literatura consultada, se reportan diferencias en el consumo de materia seca (CMS) en un rango del 9-30% entre animales eficientes e ineficientes, manteniendo una ganancia diaria de peso (GDP) similar empleando el índice CAR. Por otro lado, utilizando el índice GIR los CMS son similares, aunque la GDP en animales eficientes es mayor hasta en 50 g día^{-1}, reduciendo la conversión alimenticia en un kilogramo. Esta diferencia se asume a un conjunto de genes asociados a la eficiencia alimenticia (*Adra2a*, *Gfra1*, *Gh*, *Glis1*, *Il1rapl1*, *Lep*, *Lepr*, *Mc4r*, *Oxsm*, *Pde8b*, *Rarb*, *Ryr2*, *Sox5* y *Sox6*, *Trdn*), que pudieran ser utilizados para la selección de ovinos de razas de pelo con alta eficiencia alimenticia, teniendo en cuenta los genes relacionados con la calidad de carne (*Capns1*, *Cast*, *Dgat1*, *Fabp4*, *Igf-i*, *Lep*, *Mstn* y *Scd*).

Palabras clave.

Eficiencia alimenticia, calidad de carne, genes, ovinos de pelo.

Abstract.

The hair sheep breeds play an important role in meat production in tropical climates, where feed efficiency studies have been poorly evaluated. The feed intake represents more than 70% of costs; therefore, selection of animals with high feed efficiency can improve the profitability of sheep production system. Tools have been developed to select individuals with greater feeding efficiency without compromising the meat quality. Therefore, this review aims at identifying the genetic-molecular and statistical tools, such as, the residual feed intake (RFI) and residual intake and gain (RIG). In the literature revised, differences in dry matter intake (DMI) in a range of 9-30% are reported between efficient and inefficient animals, maintaining a similar average daily weight gain (ADG) using the RFI index. On the other hand, using the RIG index, the DMI are similar, although the ADG in efficient animals is higher by up to 50 g day^{-1}, reducing the feed conversion ratio (FCR) by one kilogram. This difference is assumed to a set of genes associated with feed efficiency (*Adra2a*, *Gfra1*, *Gh*, *Glis1*, *Il1rapl1*, *Lep*, *Lepr*, *Mc4r*, *Oxsm*, *Pde8b*, *Rarb*, *Ryr2*, *Sox5* y *Sox6*, *Trdn*), which could be used for hair breeds selection with high feed efficiency, taking into account the genes related to meat quality (*Capns1*, *Cast*, *Dgat1*, *Fabp4*, *Igf-i*, *Lep*, *Mstn* y *Scd*).

Key words.

Feed efficiency, meat quality, genes, sheep hair.

Introducción.

La población mundial de ovejas en 2017 fue de 1, 202 millones de cabezas, cerca del 74% de la población se encuentra distribuida en los continentes Asiático y Africano (42.25 y 31.70 %, respectivamente), y el 26% restante se ubica en los demás continentes, siendo el continente Americano el que menor población presenta, con 6.76% (FAO, 2020).

En México, la producción ovina es una de las actividades pecuarias con mayor presencia en su distribución territorial; las cifras preliminares del 2018 indican que la población ovina alcanzó un total de 8.7 millones de cabezas (SIAP, 2020), las cuales representan cerca del 11% de la población del continente Americano, siendo la raza Pelibuey una de las más numerosas, ya que es utilizada como pie de cría por su habilidad materna, alta prolificidad, rusticidad, resistencia a parásitos y su gran adaptación a las diversas condiciones climáticas presentes en el país, para la producción cárnica (Chay-Canul *et al*., 2016).

Por otro lado, el consumo de alimento es uno de los factores más importantes en los sistemas intensivos de producción de carne ovina, y representa más del 70% de los costos totales de producción (Lima *et al*., 2017). Por ello, la selección de animales eficientes en la utilización del alimento, que presenten una menor ingesta de alimento, manteniendo su rendimiento o incrementando la producción con una ingesta similar, podría incrementar la rentabilidad de las unidades de producción (Ellison *et al*., 2017). Esto es importante, debido a que la reducción de los costos de alimentación contribuiría a mantener los precios rentables dentro de un mercado de insumos agrícolas fluctuantes y la competitividad en el mercado global.

Tradicionalmente en la industria ganadera de producción de carne, se ha empleado la conversión alimenticia como medida de eficiencia alimenticia (Cantalapiedra-Hijar *et al*., 2018). Sin embargo, esta medida es cuestionable, debido a que el consumo de materia seca (CMS) guarda una alta correlación con el tamaño corporal y el nivel de producción (Arthur & Herd, 2008), tendiendo a seleccionar animales que presentan una ganancia diaria de peso (GDP) alta, sin embargo, también se seleccionan animales con un alto CMS, incrementando los costos de producción (Cantalapiedra-Hijar *et al*., 2018).

Otro enfoque de eficiencia alimenticia ha sido propuesto por otros autores, definiéndola como la capacidad del animal para alcanzar un determinado peso con un menor CMS (Koch *et al*., 1963). En los rumiantes la eficiencia es baja comparada con otras especies, no obstante, tienen la capacidad de transformar recursos no comestibles para el ser humano (forrajes y nitrógeno no proteico) en alimentos de alta calidad (Cantalapiedra-Hijar *et al*., 2018).

En consecuencia, se han buscado diversas herramientas que ayuden a explicar, predecir y seleccionar a los individuos con mayor eficiencia en la utilización del alimento y de la energía consumida. Entre estas, el consumo de alimento residual (CAR) o "Residual Feed Intake" (RFI, por sus siglas en inglés), es una de las más empleadas (Koch *et al*., 1963; Bezerra *et al*., 2013). El CAR, está definido como la diferencia entre el consumo de alimento real y el consumo de alimento esperado para un peso y nivel productivo determinado durante un periodo específico (Arthur & Herd, 2008; Fitzsimons *et al*., 2014a). Su objetivo es identificar a los animales más eficientes en la utilización de alimento y con esto lograr una mejora genética del hato ganadero, además, de reducir los costos de la producción de cada kilogramo de peso vivo incrementado (Arthur & Herd, 2008). Además del CAR, Koch *et al*. (1963) propusieron el índice Ganancia residual (GR) o "Residual Gain", el cual permite estimar la ganancia esperada para un nivel productivo, con el objetivo de identificar a los animales con las mayores tasas de ganancia de peso.

Recientemente, ha sido propuesto un nuevo indicador de eficiencia alimenticia denominado Ganancia e Ingesta Residual (GIR) o "Residual Intake and Gain" (RIG, por sus siglas en inglés). Este indicador de eficiencia alimenticia conserva la característica de selección de CAR y GR, que son independientes del peso corporal. El GIR permite seleccionar animales que presentan mayores GDP y menor CMS, debido a que el GIR se correlaciona negativamente con el CMS y positivamente con la GDP (Berry & Crowley, 2012).

El interés de la industria cárnica no solo es en la eficiencia del uso del alimento, sino también en la calidad del producto destinado al mercado. La calidad de la carne se compone de varios rasgos, incluidos los atributos fisicoquímicos (terneza, color, contenido de grasa intramuscular y la capacidad de retención de agua) y los factores que afectan la palatabilidad (sabor, jugosidad y olor), así como las características de inocuidad (Becker, 2000), los cuales influyen en la toma de decisión del cliente al elegir un tipo de corte, así como también para la industria en el procesamiento de la carne (Grochowska *et al*., 2017). En este sentido, se han realizado diversos estudios que emplearon la herramienta CAR para determinar el efecto de la eficiencia alimenticia sobre la calidad de la carne, reportando que la selección de bovinos Angus eficientes (bajo CAR) no afecta negativamente la calidad de carne producida (Baker *et al*., 2006; Perkins *et al*., 2014). Sin embargo, existe controversia en los resultados en estudios recientes en bovinos Nelore, ya que se han reportado que la eficiencia no afecta la calidad de la carne y la actividad del sistema

Calpaina (Gomes *et al*., 2012; Fidelis *et al*., 2017), mientras que otros estudios indican lo contrario. En consecuencia, los animales con bajo CAR tienden a presentar mayor dureza de su carne (Zorzi *et al*., 2013), y se ha indicado que esta característica indeseable está regulada por el recambio proteico y la expresión génica de ciertas enzimas (principalmente por el sistema de las Calpaínas) encargadas de la proteólisis *postmorten* del músculo (Koohmaraie *et al*., 2002). Así mismo, se ha documentado que la degradación de la proteína está relacionada con la energía requerida para el mantenimiento (REMm) y una alta tasa de degradación proteica está asociada con un REMm mayor (Castro-Bulle *et al*., 2007). En este sentido, los animales más eficientes tienen un menor requerimiento de energía metabolizable para el mantenimiento (Castro-Bulle *et al*., 2007; Gomes *et al*., 2012), y presentan una baja tasa de degradación proteica (McDonagh *et al*., 2001), lo que se relaciona con una mayor fuerza de corte a diferentes tiempos de maduración (0 d= 4.50 vs 4.00, 7 d= 4.22 vs 3.61, 21 d= 3.27 vs 2.69 kg/cm^2), bajo índice de fragmentación miofibrilar (37.0 vs 42 %) y alto contenido de colágeno soluble (17.7 vs 14.9 %) en ganado Nelore con bajo CAR, presentando carne de menor calidad (Zorzi *et al*., 2013).

Por otro lado, con el desarrollo de la genética molecular, secuenciación y técnicas moleculares de amplificación de regiones genómicas selectivas, se ha aumentado las posibilidades de detectar genes que tienen un efecto notable en los rasgos de interés (ej. eficiencia alimenticia y calidad de carne), detectando secuencias genómicas vinculados a estos genes y la posibilidad de establecer programas de selección con marcadores moleculares, prediciendo los valores de mejora para los individuos seleccionados al momento del nacimiento con una precisión mayor que el índice de pedigrí clásico, y reduciendo el intervalo generacional (Blasco & Toro, 2014). Por lo tanto, el objetivo de este trabajo fue realizar una revisión sobre índices de eficiencia alimenticia y su relación con la calidad de carne y genes asociados a estos rasgos en ovinos de pelo.

Índices de eficiencia alimenticia.

Koch *et al*. (1963) observaron que el mantenimiento de peso vivo y la ganancia diaria de peso son afectados por la alimentación. Propusieron que el consumo de alimento puede ajustarse al peso corporal y a la ganancia de peso, dividiendo el consumo de alimento en dos componentes: 1) el consumo de alimento esperado para un rendimiento o nivel de producción dado, y 2) una porción residual. La porción residual del consumo de alimento podría usarse para identificar animales que se desvían hacia abajo de su nivel esperado de consumo de alimento (CAR negativo), permitiendo realizar una comparación entre los animales que difieren en el nivel de producción durante el periodo de medición.

El CAR se ha utilizado como criterio de selección en programas de mejora genética en ganado de carne, ya que la heredabilidad estimada de esta característica es moderada ($h^2 \approx 0.33$) e independiente del crecimiento y del nivel productivo (Koch *et al*., 1963; Herd & Arthur, 2009; Berry & Crowley, 2012).

Así mismo, el CAR reduce el impacto de la ganadería al medio ambiente, ya que individuos con bajo CAR tienden a producir menor cantidad de metano (CH_4) por unidad de materia seca consumida, debido al menor CMS y mejor eficiencia en el uso de la energía (Nkrumah *et al*., 2006; Fitzsimons *et al*., 2013). Es por ello que el CAR representa una de las estrategias de mitigación en las emisiones de dióxido de carbono metabólico (CO_2) y CH_4 de la actividad ganadera al ambiente.

El nuevo índice GIR, además de tener como ventaja la mejora en la eficiencia en la alimentación, permite identificar animales con mayores tasas de crecimiento y una menor proporción de grasa, sin afectar la calidad de la carne y canal; reduciendo los tiempos de confinamiento y sacrificio de los animales, con pesos comerciales a edades tempranas (Berry & Crowley, 2012; Carneiro *et al*., 2019).

Los estudios que involucran los índices CAR y GIR, han sido realizados principalmente en bovinos, porcinos y aves. En el caso de ovinos se han realizado en razas de clima templado; aunque, se han reportado cuatro estudios que involucran cruzas de ovinos de pelo de razas brasileñas (Tabla 1.1 y 1.2), destacando la raza Santa Inés y Pantaneira (Lima *et al*., 2017; Rocha *et al*., 2018; Carneiro *et al*., 2019; Montelli *et al*., 2019), y un estudio en la raza Dorper (Paula *et al*., 2012). En México se comienza a implementar esta herramienta por lo que el número de estudios es reducido, y en ovinos solo se tiene el trabajo realizado con la raza Rambouillet (Muro-Reyes *et al*., 2011), por lo que se desconoce el comportamiento en los ovinos de pelo tropicales (Tabla 1.1).

Estimación de los indicadores CAR y GIR.

El CAR, nos permite determinar el CMS esperado, y es estimado a través de una ecuación de regresión lineal múltiple en función del peso medio metabólico (PMM) y la GDP.

El modelo utilizado por Koch *et al*. (1963), se muestra a continuación:

$$Y_i = \beta_0 + \beta_1 GDP_i + \beta_2 PMM_i + \varepsilon_i$$

Donde, Y_i es la ingesta de materia seca del i-ésimo animal, β_0 es el intercepto de la regresión, $\beta_1 GDP_i$ es el coeficiente de regresión parcial de la ingesta de materia seca en la i-ésima ganancia diaria de peso del animal, $\beta_2 PMM_i$ es el coeficiente de regresión parcial de ingesta de materia seca del i-ésimo peso medio metabólico del animal y, ε_i es el error residual en la ingesta de materia seca del i-ésimo animal.

Por otro lado, GR nos ayuda a estimar la GDP esperada, mediante regresión lineal múltiple en función del CMS y PMM.

$$Y_i = \beta_0 + \beta_1 CMS_i + \beta_2 PMM_i + \mathcal{E}_i$$

Donde, Y_i es la ganancia de peso del i-ésimo animal, β_0 es el intercepto de la regresión, $\beta_1 CMS_i$ es el coeficiente de regresión parcial de la ganancia diaria de peso del i-ésimo consumo de materia seca del animal, $\beta_2 PMM_i$ es el coeficiente de regresión parcial de la ganancia diaria de peso del i-ésimo peso medio metabólico del animal, y ε_i es el error residual en la ganancia diaria de peso del i-ésimo animal.

Para el cálculo de GIR, se utiliza los dos modelos antes descritos, empleando la siguiente fórmula: GIR = (CAR*-1) + GR. El índice requiere una previa estandarización (Media = 0 y Desviación estándar = 1) del CAR y GR (Berry & Crowley, 2012.

Después de determinar el CAR, los animales son clasificados en grupos de CAR alto (>0.5 DE por encima de la media, mayor consumo de alimento de lo esperado para el mantenimiento y producción, por lo tanto, menor eficiencia), CAR medio (±0.5 DE de la media) y CAR bajo (<0.5 DE por debajo de la media, menor consumo de alimento de lo esperado, por lo tanto, mayor eficiencia). El mismo procedimiento de categorización se utiliza para determinar los grupos GIR, sin embargo, un alto GIR nos indica mayor eficiencia y un bajo GIR menor eficiencia.

Factores fisiológicos que intervienen.

Los mecanismos fisiológicos que están relacionados con una mayor eficiencia en el uso del alimento son numerosos e interrelacionados, sin embargo, no están completamente dilucidados. Richardson y Herd (2004), proporcionaron una síntesis de los resultados de una serie de experimentos en bovinos de la raza Angus seleccionados de forma divergente para CAR, y estimaron la proporción de la variación en CAR que explican los siguientes procesos: el recambio proteico, metabolismo y estrés tisular (37%), digestibilidad (10%), incremento de calor y fermentación (9%), actividad física (9%), composición corporal (5%) y patrones de alimentación (2%). Los mecanismos responsables de más de un cuarto de la variación en CAR todavía no se conocen. Posteriormente, estos procesos fisiológicos del animal que se asocian a la variación en la eficiencia en la utilización del alimento se agruparon en cinco categorías 1) la capacidad de ingesta de alimento, 2) la digestión del alimento, 3) el metabolismo (anabolismo y catabolismo), 4) producción de calor relacionado con la digestión de la dieta y la actividad física, y 5) la termorregulación (Herd & Arthur, 2009).

Conocer los procesos fisiológicos implicados y el grado en que estos contribuyen en la eficiencia alimenticia de los ovinos de pelo, es de vital importancia, ya que en estas razas es escaza la información. Por lo que es necesario, emprender estudios que ayuden a dilucidar como estos mecanismos favorecen este comportamiento. De esta manera, se podrá seleccionar individuos más eficientes y de mayor productividad.

Consumo de alimento y comportamiento productivo.

El consumo voluntario de alimento del ganado está regulado por una interacción compleja entre mecanismos de control neuroendócrino, las propiedades fisicoquímicas del alimento, y el estado fisiológico del animal (Allen, 2020). Por otra parte, existe una relación entre la ingesta del alimento y la energía que se gasta para digerirse. A medida que se incremente la ingesta, mayor será el gasto energético; esto se debe a un aumento en el tamaño de los órganos digestivos y a la energía gastada dentro de los tejidos de dichos órganos (Herd & Arthur, 2009); a este gasto energético se le conoce como incremento de calor en la fermentación, y en rumiantes es aproximadamente el 9% de la ingesta de la energía metabolizable (Standing Committee Agriculture, 2000).

La mayoría de los estudios (Tabla 1.1) indican que los ovinos con CAR bajo tienen la misma GDP que animales con CAR alto, debido a que los animales con bajo CAR tienen una mejor eficiencia en el uso de la energía (Fitzsimons *et al*., 2013). Sin embargo, Rocha *et al*. (2018) reportaron diferencias significativas en la GDP, haciendo más notoria la eficiencia en la utilización de la energía; en todos los estudios el CMS fue menor en los animales más eficientes, observándose una diferencia que varía en un rango de 9 a 30% comparado con los menos eficientes. De este modo, es de esperar que los animales más eficientes presenten una mejor conversión alimenticia (Tabla 1.1).

Empleando el índice GIR en los estudios realizados en ovinos (Lima *et al*., 2017; Carneiro *et al*., 2019; Montelli *et al*., 2019), se observa que los ovinos clasificados con un alto GIR presentan un menor CMS, mayor GDP, mejor conversión alimenticia y mayor eficiencia alimenticia (EA) (Tabla 1.2). Aunque la diferencia en el CMS no es tan amplia como en la observada con el CAR, en la GDP se observa una diferencia de hasta 50 g d^{-1}. Por otro lado, la diferencia en la conversión alimenticia es de más de un kilogramo, por lo que la EA es mayor en los animales con GIR alto. Desde el punto de vista productivo, un menor consumo de alimento y mayores ganancias de peso representan una importante reducción en los costos de operación, aumento de la rentabilidad de las unidades de producción y uso eficiente de la energía suministrada, considerando que la alimentación representa el mayor costo de producción en los sistemas de producción animal.

Producción de metano.

El ecosistema microbiano del rumen es extremadamente diverso, habitado por filotipos de los dominios Eucariota, Arqueas y Bacterias interactuando entre ellos, el alimento y el hospedero, con densidades de 10^{10} bacterias mL^{-1}, 10^{6} protozoos mL^{-1}, y 10^{3} hongos mL^{-1} de fluido ruminal (Singh *et al*., 2019).

La dieta es considerada como la principal determinante de diversidad de microorganismos ruminales y del parámetro de fermentación en bovinos y ovinos (Carberry *et al*., 2012). En este sentido, los animales alimentados con forraje tienen un ecosistema microbiano más diverso y es más frecuente encontrar grupos metanogénicos, en comparación con aquellos con dieta alta en concentrados (Ellison *et al*., 2014).

Tabla 1.1 Parámetros productivos en ovinos clasificados por consumo de alimento residual (CAR).

Razas	Consumo de alimento residual									DCMS	Autor
	Bajo	Medio	Alto	Bajo	Medio	Alto	Bajo	Medio	Alto	DCMS	
	Ganancia diaria de peso			Consumo de materia seca			Conversión alimenticia			%	
½D½SI	0.280	-	0.270	1.24^{b}	-	1.41^{a}	4.43^{b}	-	5.15^{a}	12.06	Lima *et al.*, 2017
RHS	0.260	-	0.240	2.23^{b}	-	3.22^{a}	-	-	-	30.74	Ellison *et al.*, 2017
¾T¼P	0.321^{a}	0.277^{b}	0.306^{ab}	1.34^{b}	1.35^{b}	1.52^{b}	4.18^{a}	4.90^{b}	5.00^{b}	11.84	Rocha *et al.*, 2018
½D½SI	0.284	0.301	0.286	1.25**	1.37**	1.44**	-	-	-	13.19	Montelli *et al.*, 2019
Dorper	0.266		0.253	2.63^{b}		3.00^{a}	5.94^{b}		6.91^{a}	12.33	Paula *et al.*, 2012
Rambouillet	0.180	0.170	0.180	1.39^{c}	1.48^{b}	1.67^{a}	-	-	-	16.77	Muro-Reyes *et al.*, 2011
Targhee	0.350	0.330	0.360	1.92^{b}	2.02^{b}	2.32^{a}	6.58^{b}	7.71^{a}	7.83^{a}	17.24	Redden *et al.*, 2011
Ghezel	0.210	-	0.200	1.01^{b}	-	1.12^{a}	4.95^{b}	-	5.53^{a}	9.82	Rajai-Sharifabadi *et al.*, 2012

Ile de France	0.329	-	0.335	1.42[b]	-	1.63[a]	4.35	-	4.93	12.88	Paula *et al.*, 2013
Targhee	0.297	0.302	0.286	2.15[b]	2.31[b]	2.52[a]	-	-	-	14.68	Redden *et al.*, 2013
Targhee	0.294	-	0.293	2.21[b]	-	2.43[a]	-	-	-	9.05	Redden *et al.*, 2014
RHS	-	-	-	2.10[b]	-	2.89[a]	-	-	-	27.34	Meyer *et al.*, 2015
Kurdi	0.260	-	0.260	1.82[b]	-	2.11[a]	-	-	-	13.74	Rajai-Sharifabadi *et al.*, 2016
Hu	0.280	-	0.250	1.50[b]	-	1.72[a]	-	-	-	12.80	Liang *et al.*, 2017
Ghezel	0.280	-	0.290	1.52[b]	-	1.72[a]	5.47	-	5.93	11.63	Zamiri *et al.*, 2017
Hu	0.250	0.260	0.260	1.09[c]	1.25[b]	1.33[a]	4.51[c]	4.84[b]	5.39[a]	18.04	Zhang *et al.*, 2017
Hu	0.260	-	0.270	1.05[b]	-	1.48[a]	3.92[b]	-	5.62[a]	29.05	Zhang *et al.*, 2019

DCMS= Diferencia en el consumo de materia seca (%), ½D½SI= ½Dorper ½Santa Inés, RHS= Rambouillet, Hampshire y Suffolk, ¾T¼P= ¾Texel ¼Pantaneira, **, [abc]= Diferencias significativas.

Tabla 1.2 Parámetros productivos en ovinos clasificados por ganancia e ingesta residual (GIR).

Raza	Ganancia e ingesta residual												Autor
	Bajo	Medio	Alto	Bajo	Medio	Alto	Bajo	Medio	Alto	Bajo	Medio	Alto	
	Consumo de materia seca			Ganancia diaria de peso			Conversión alimenticia			Eficiencia alimenticia			
½D½SI	1.39^{a}	-	1.31^{b}	0.26^{b}	-	0.30^{a}	5.32^{a}	-	4.28^{b}	0.19^{b}		0.23^{a}	Lima *et al*., 2017
¾T¼P	1.28	1.27	1.22	0.26^{b}	0.29^{a}	0.31^{a}	4.99^{a}	4.28^{b}	3.91^{c}	0.20^{c}	0.24^{b}	0.26^{a}	Carneiro *et al*., 2019
½D½SI	1.41	1.37	1.31	0.26**	0.29**	0.30**	5.36*	4.61*	4.27*	0.18*	0.21*	0.23*	Montelli *et al*., 2019

½D½SI= ½Dorper ½Santa Inés, ¾T¼P= ¾Texel ¼Pantaneira, *= Datos calculados, **$^{, abc}$= Diferencias significativas.

Estudios recientes indican que existe una relación entre la eficiencia alimenticia y la producción de CH_4 (Nkrumah *et al*., 2006; Zhou *et al*., 2009). Se ha reportado que las comunidades metanogénicas en animales con alto CAR son más diversas comparadas con los individuos eficientes, presentando una alta prevalencia de *Methanosphaera stadtmaniae* y *Methanobrevibacter sp.* En este sentido, los animales con CAR alto tienen mayores emisiones de CO_2 metabólico y CH_4, esto es debido al mayor consumo de compuestos fibrosos, los cuales aumentan la producción de CH_4 ruminal. En animales con CAR bajo, se ha observado que tienden a modificar los consorcios bacterianos, por lo cual utilizan los compuestos fibrosos de la ración con más eficiencia, reduciendo con esto la tasa de pasaje y aumentando la digestibilidad, fermentando completamente las raciones a nivel ruminal (Zhou *et al*., 2009).

En ovinos, se han reportado diferencia significativa en emisiones de CH_4 en hembras utilizando modelos estadísticos de predicción, siendo menores en aquellas con CAR bajo y CAR medio comparadas contra CAR alto (0.025^a. 0.028^a y 0.032^b CH_4 kg^{-1} d^{-1}, respectivamente). Sin embargo, no encontraron diferencias estadísticas en machos para emisiones de CH_4, debido a una pobre diferencia observada en el CMS entre animales eficientes e ineficientes (Muro-Reyes *et al*., 2011). Así mismo, una mayor eficiencia podría estar relacionada con la presencia de bacterias que modifican el patrón de fermentación hacia una fermentación más propiónica, lo cual favorece la ganancia de peso (Fitzsimons *et al*., 2013). El propionato es considerado el principal sustrato contribuyente al proceso de gluconeogénesis y formación de glucosa, la cual es requerida como fuente de energía en la síntesis de proteína (Allen, 2020). En este sentido, Ellison *et al*. (2017) reportaron una mayor concentración de propionato en ovinos altamente eficientes (CAR bajo) alimentados con concentrados, comparado con los menos eficientes (41.2 vs 30.2 % Molar).

Por lo tanto, la selección de animales a través de los índices de eficiencia alimenticia, también podría contribuir con la reducción de la emisión de gases de efecto invernadero (GEI) producidas por la ganadería ovina.

Genes candidatos asociados a eficiencia alimenticia.

Diversos estudios han reportado una gran cantidad de polimorfismos de un solo nucleótido (SNP por sus siglas en inglés, "Single Nucleotide Polymorphism") asociados con la eficiencia alimenticia en bovinos (Abo-Ismail *et al*., 2018; Duarte *et al*., 2019), aunque son pocos los trabajos en ovinos. Conocer o determinar los genes que están asociados u implicados en los procesos biológicos relacionados con características productivas deseables (eficiencia alimenticia y calidad de carne) de los animales domésticos, ayuda a entender la relación entre estos parámetros para utilizar estos genes como marcadores moleculares para la selección de animales con que pueden trasmitir características deseadas a su progenie (Tabla 1.3).

Cockrum *et al*. (2012) identificaron marcadores mediante el análisis de asociación del genoma completo (GWAS) que alcanzaron un umbral nominal $P < 3.02^{-4}$ en genes ovinos asociados a CAR, siendo los genes de la Familia Dedos de Zinc 1 (*Glis1*), Factor de transcripción SRY caja -5 y -6 (*Sox5*, *Sox6*) y la Proteína Accesoria 1 del Receptor de Interleucina (*Il1rapl1*), los genes candidatos. Jonas *et al*. (2016) reportaron la asociación de un SNP en el exón 2 del Receptor de Leptina (*Lepr*) en ovejas en etapa de lactación ($p<0.05$), siendo el genotipo homocigoto CC con mayor CAR (2.579[a]) comparado con los genotipos TC (1.218[b]) y TT (1.005[b]).

Estudios recientes han reportado la asociación de la GDP con SNP´s de genes que pueden ser considerados en la selección de animales con mejor desempeño productivo. Por ejemplo, Zhang *et al*. (2013) identificaron el gen Triadina (*Trdn*) ubicado en el cromosoma 8, y en el cromosoma 26 los genes 3-Oxoacil-ACP Sintasa (*Oxsm*) y el Receptor de Ácido Retinoico Beta (*Rarb*). Así mismo, se ha relacionado el gen Leptina (*Lep*) con GDP (Hajihosseinlo *et al*., 2012), con diferencias significativas (P<0.05) en la GDP (destete-seis meses) en los genotipos heterocigoto BC, AB y AC que en los homocigotos AA y CC (116, 103, 99, 94 y 94 g d^{-1}, respectivamente).

Gorlov *et al*., (2017) identificaron en la raza Salsk una relación de la GDP con los genotipos de la Hormona del Crecimiento (*Gh*), siendo el genotipo AB superior al AA (128.64 vs 81.51 g $día^{-1}$). También, se ha asociado al gen Receptor de Melanocortina-4 (*Mc4r*) con la GDP, donde un SNP localizando en la región no traducida 3´ del gen (NM_001126370.2) provoca una variación del nucleótido en la posición 1016 G>A, observándose que el genotipo heterocigoto GA fue superior al homocigoto GG a los 120 d (210.23 vs 192.01 g d^{-1}) y 180 d (166.35 vs 155.66 g d^{-1}) de engorda; así mismo se detectó el SNP 292 G>A con una variación en el aminoácido 98 Gly>Arg, el cual tuvo efecto sobre el área del músculo *Longissimuss dorsi* o ribeye (Zou *et al*., 2014).

Se ha reportado la asociación de la conversión alimenticia con algunos genes. En el exón 3 del gen *Lep* en ovejas lactantes, se encontraron diferencias significativas (P<0.001) en los genotipos de un SNP con variación en aminoácidos (c.314 G>A, Arg>Gln); el genotipo GG presentó menor conversión alimenticia (2.019 kg) comparada con el genotipo AG (3.886 kg) en la producción de leche (Jonas *et al*., 2016). Así mismo, Zhang *et al*., (2019) identificaron un efecto positivo de dos mutaciones sinónimas g.1429 C>A y g.1117 A>C en los genes Adrenoreceptor alfa 2A (*Adra2a*) y Receptor de Rianodina 2 (*Ryr2*) con este indicador de eficiencia, en *Adra2a* se identificaron tres genotipos CC, CA y AA, donde el homocigoto CC presentó menor conversión alimenticia (4.67[b], 5.18[a] y 5.14[a] kg, respectivamente). Por su parte en *Ryr2*, fueron identificados genotipos similares, aunque el homocigoto presentó menor conversión alimenticia pero estadísticamente fue similar al genotipo CC (5.14[b], 5.08[b] y 5.46[a] kg, respectivamente).

Tabla 1.3 Genes asociados a eficiencia alimenticia y calidad de carne en ovinos.

Símbolo	Gen	Crom	Proceso biológico	Par	Autor
Glis1	*Glis* Familia Dedos de Zinc 1	1	Promotor de la reprogramación de fibroblastos en humanos y ratón, en células madre pluripotentes inducidas durante el desarrollo embrionario. Además, está asociado en la regulación de genes (*Foxa2*, *Wnt* y *Esrrb*) implicados en la transición mesenquimal-epitelial, un proceso crítico en la reprogramación de las células somáticas (Maekawa *et al*., 2011).	CAR	Cockrum *et al*. (2012)
Sox5 y *Sox6*	Factor de transcripción SRY caja -5 y -6	15	Su expresión está relacionada con un proceso eficiente de la condrogénesis (desarrollo del cartílago), aunque se requiere del gen *Sox9* para activar y mantener genes específicos de condrocitos. Los genes *Sox5* y *Sox6* aumentan notablemente la actividad transcripcional de *Sox9*, asegurando su unión al ADN (Han *et al*., 2008).		
Il1rapl1	Proteína Accesoria 1 del	X	Relacionado con la discapacidad intelectual y trastornos del espectro autista promovido por la ausencia de la proteína de		

	Receptor de Interleucina 1		*Il1rapl1*. Las mutaciones en *Il1rapl1* causan la ausencia de la proteína o la producción de una proteína disfuncional en humanos (Montani *et al*., 2019).		
Lepr	Receptor de Leptina	1	Produce una proteína, que al unirse con la Leptina desencadenan una serie de señales químicas (vía de señalización JAK/STAT) causando la activación del receptor y la transfosforilación de las moléculas JAK asociadas al receptor, promoviendo la homeostasis energética (Ladyman & Grattan, 2013).	CAR	Jonas *et al*. (2016)
Trdn	Triadina	8	Contribuye a la regulación de la liberación de Ca^{2+} a través de los canales de liberación de calcio del retículo sarcoplásmico *Ryr2* y *Casq2*, un paso clave para desencadenar la contracción del músculo esquelético y cardíaco; su ausencia es responsable de la arritmia cardiaca con muerte súbita en humanos (Roux-Buisson *et al*., 2012).	GDP	

Oxsm	3-Oxoacil-ACP Sintasa Mitocondrial	26	Enzima relacionada con la vía sintética de ácido α-lipoico, su actividad es necesaria para el alargamiento de las cadenas de ácidos grasos en la producción de ácido α-lipoico. La deficiencia del ácido α-lipoico representa un factor de riesgo en la patogenia diabética (Gao *et al*., 2019).	GDP	Zhang *et al*. (2013)
Rarb	Receptor de ácido Retinoico Beta	26	Los receptores de ácido retinoico son esenciales para la señalización de ácido retinoico durante el desarrollo embrionario y la organogénesis (Mark *et al*., 2006).	GDP	
Lep	Leptina	4	Hormona sintetizada por el tejido adipocito que desempeña un papel importante en la regulación del apetito y el metabolismo de la energía. Además, se ha relacionado con la deposición de grasa en mamíferos (Houseknecht & Portocarrero, 1998).	GDP CAL Ph TER	Hajihosseinlo *et al*. (2012) Jonas *et al*. (2016) Boucher *et al*. (2006)
Gh	Hormona del Crecimiento	11	Activación de procesos anabólicos, regulando el aumento en el tamaño corporal y el crecimiento esquelético (Akers, 2006).	GDP	Gorlov *et al*. (2017)
Mc4r	Receptor de Melanocortina 4	23	Receptor que se expresa predominantemente en el núcleo hipotalámico regulador del apetito, su importancia radica en la	GDP	Zou *et al*. (2014)

			regulación de la ingesta de alimentos y la homeostasis energética (Cone, 2005).		
Adra2a	Adrenoreceptor Alfa 2ª	22	Regulador de las catecolaminas, asociado con el metabolismo energético. Además, participa en la vía de la adrenalina y puede regular el metabolismo energético a través de la secreción de adrenalina (Lima *et al*., 2007).	CAL	Zhang *et al*. (2019)
Ryr2	Receptor de Rianodina 2	25	Principal canal de liberación de Ca^{2+} del retículo sarcoplasmático en los miocitos ventriculares, relacionada con enfermedades cardiacas (Roux-Buisson *et al*., 2012).	CAL	
Pde8b	Fosfodiesterasa 8B	7	Codifica una fosfodiesterasa específica de adenosín monofosfato cíclico, como moduladores genéticos de los niveles de la hormona estimulante de la tiroides (Hayashi *et al*., 1998). La tiroides (sintetiza tiroxina) controla procesos biológicos, entre ellos la expresión génica, el crecimiento, el desarrollo y el metabolismo (Kopp, 2005).	EA	Alvarenga *et al*. (2016)

Gfra1	Familia GDNF Receptor Alfa 1	22	Efecto sobre el receptor de tirosina quinasa, el cual regula la proliferación celular, factores de crecimiento, desarrollo y diferenciación neuronal (Paratcha *et al*., 2001).	EA	
Fabp4	Proteína de Unión a Ácidos Grasos, Adipocito	9	Conocidas como chaperonas lipídicas intracelulares, las cuales unen y transportan ácidos grasos de cadena larga en mamíferos, además de estar asociado con el crecimiento, la deposición de grasa y los rasgos de la canal en el ganado (Yan *et al*., 2018).	Ph TER CRA	Xu *et al*. (2011)
Capns1	Calpaina Subunidad 1	14	Principalmente asociado con la degradación de las proteínas miofibrilares *post-morten*, ocasionando ablandamiento de la carne (Koohmaraie *et al*., 2002).	CRA COL	Grochowska *et al*. (2017)
Cast	Calpastatina	5	Enzima que inhibe la acción de las calpainas, está relacionada con la regulación de la degradación proteica muscular. La inhibición de la degradación proteica muscular por el sistema calpastatina, incrementa la eficiencia productiva, pero induce un impacto en la terneza o suavidad de la carne producida (Koohmaraie *et al*., 2002).	TER CRA COL	Aali *et al*. (2017) Jawasreh *et al*. (2017) Jawasreh *et al*., 2017

Dgat1	Diacilglicerol O-Aciltransferasa 1	9	Enzima moduladora de la síntesis de triglicéridos y regulación del flujo de triglicéridos en el cuerpo, así mismo, tiene implicaciones directas en el metabolismo de la glucosa y la enfermedad de la obesidad, resistencia a la insulina y la esteatosis hepática (Yen *et al*., 2008).	TER CRA	Xu *et al*. (2009)
Igf-1	Insulina como Factor de Crecimiento 1	3	Involucrado en el control del crecimiento esquelético y la diferenciación celular mediante la activación del ciclo celular (Rechler & Nisseley, 1991).	CRA	Grochowska *et al*. (2017)
Mstn	Miostatina	2	La miostatina regulador de la masa muscular en mamíferos, siendo las mutaciones naturales en *Mstn* las que inactivan la proteína codificada o suprimen su cantidad provocando un aumento de la musculatura (Tellam *et al*., 2012).	CRA	Grochowska *et al*. (2019)
Scd	Estearoil-CoA Desaturasa	22	Regulador de la síntesis y oxidación lipídica (Sampath & Ntambi, 2006).	COL	Aali *et al*. (2016)

Crom= Cromosoma, Par= Parámetro, CAR= consumo de alimento residual, GDP= ganancia diaria de peso, CAL= conversión alimenticia, TER= terneza, EA= eficiencia alimenticia, CRA= capacidad de retención de agua, COL= color.

Recientemente, se reportó la asociación de los genes de la Familia *GDNF* Receptor Alfa 1 (*Gfra1*) y gen Fosfodiesterasa (*Pde8b*) con la EA en ovinos Santa Inés (Alvarenga *et al*., 2016).

Los genes implicados en la eficiencia alimenticia pueden ser de gran ayuda para identificar mediante técnicas moleculares a los individuos superiores. Estas técnicas, han sido pobremente empleadas en los ovinos de pelo, por lo que su uso permitirá identificar y seleccionar a muy temprana edad aquellos individuos con mayor eficiencia alimenticia, reduciendo el intervalo generacional.

Calidad de carne y genes candidatos asociados.

Los resultados en estudios realizados en ovinos, sugieren que las características de la canal (área del *longissimus*, espesor de la grasa subcutánea y profundidad del músculo *longissimus*), no se ven afectados negativamente al seleccionar por el índice CAR (Paula *et al*., 2012; Rajai-Sharifabadi *et al*., 2012; Paula *et al*., 2013; Redden *et al*., 2013; Redden *et al*., 2014; Rajai-Sharifabadi *et al*., 2016; Lima *et al*., 2017; Rocha *et al*., 2018), mientras que, existen tendencias ($P<0.1$) a un mayor rendimiento de la canal en los corderos eficientes (Zhang *et al*., 2017; Rocha *et al*., 2018).

Por otro lado, se han reportado la asociación de genes con los parámetros físico-químicos que determinan la calidad de la carne, tales como el pH, terneza, capacidad de retención de agua, y color.

pH.

En los pequeños rumiantes un pH normal para la carne debe estar en un rango de 5.5 a 5.8 (Almeida *et al*., 2017), y está relacionado con las características deseables en la calidad de la carne, como el color, fuerza de corte y capacidad de retención de agua.

Algunos estudios han demostrado la relación que existe entre el pH y el polimorfismo de algunos genes. Se ha informado la asociación del gen *Lep* (intrón 2, g.103 A>G) en la raza Suffolk (Boucher *et al*., 2006), identificando los genotipos AA y AG, siendo el genotipo homocigoto que presentó menor pH 5.53 vs 5.70 para el heterocigoto ($P<0.05$). Por otro lado, se identificaron genotipos del gen de la Proteína de Unión a Ácidos Grasos (*Fabp4*) en ovejas chinas con efecto sobre el pH ($P<0.1$). El genotipo heterocigoto AG presentó menor pH (6.3), mientras que AA y GG presentaron un valor de 6.5 (Xu *et al*., 2011), aunque el pH final fue superior al reportado como deseable en la literatura.

Terneza.

A medida que comienza el proceso de rigor mortis, los sarcómeros se acortan y se produce una contracción transversal de la miofibrilla, dando como resultado un aumento de la resistencia al corte. La reducción en el espacio entre miofilamentos dentro de la miofibrilla aumenta la densidad de las proteínas en un área definida, y es probable que esta reducción de espacio, disminuya la acción enzimática de las proteasas encargadas de la degradación de proteínas miofibrilares, afectando la terneza de la carne (Warner, 2016). Se ha reportado que la actividad de las calpaínas es responsable hasta en un 90% del ablandamiento proteolítico de la carne (Gheisari *et al*., 2007).

En ovinos se ha reportado la relación de algunos genes con la fuerza de corte, destacando el gen Calpastatina (*Cast*) como el principal gen relacionado con la textura, con diferencias significativas entre los genotipos del gen *Cast* (B, C, D, I) en razas Iranies (Aali *et al*., 2017), donde el genotipo I requirió una fuerza al corte de 8.39 kg y el genotipo C una fuerza de 12.69 kg, siendo más deseable ovinos del genotipo I para este parámetro. Además, se reportó una variación en el nucleótido 197A>T en el exón 6 del gen *Cast*, provocando un cambio en el aminoácido 66 Glutamina (Gln)>Leucina (Leu), donde el genotipo heterocigoto AT presentó menor fuerza al corte que el homocigoto AA (6.68 vs 8.71 kg). Para este mismo gen, se encontró la presencia de dos genotipos en la raza Awassi (Jawasreh *et al*., 2017), con diferencias significativas ($P<0.05$) en la fuerza utilizada, presentando el genotipo MN mayor fuerza que el genotipo MM (4.36 y 3.98 kg, respectivamente). En razas chinas, se ha citado la asociación de genotipos del gen Diacilglicerol O-Aciltransferasa 1 (*Dgat1*) y la terneza (Xu *et al*., 2009), en el genotipo TT se necesitó menor fuerza que TC y CC (2.30, 2.69 y 2.73 kg). También en razas chinas, se informó el efecto de genotipos en el gen *Fabp4* con la terneza (Xu *et al*., 2011), el genotipo AA presentó mayor terneza que los genotipos AG y GG (2.24, 2.78 y 2.88 kg, respectivamente, $P<0.05$). Otro gen asociado a este parámetro es el gen *Lep*; citando el polimorfismo en este gen (intrón 2, g.103 A>G) en la raza Suffolk (Boucher *et al*., 2006), siendo el genotipo homocigoto AA quien presentó menor fuerza al corte que el genotipo AG (3.6 y 4.7 kg, respectivamente).

Capacidad de retención de agua (CRA).

La CRA es definida como la habilidad de la carne para retener toda o parte de su propia agua (Honikel, 2004), y está estrechamente relacionada con pH y el punto isoeléctrico de las proteínas musculares (pH 5.1-5, carga neta 0), por lo que, si se alcanza este punto, la CRA se reduce al mínimo (Warner, 2016).

El gen *Cast* está relacionado con la pérdida de agua por cocción, con diferencias (P<0.05) entre los genotipos MM y MN en ovinos Awassi (Jawasreh *et al*., 2017), donde el genotipo homocigoto (MM) presentó el mayor porcentaje de pérdida de agua (48.45 y 45.69%, respectivamente).

Por otro lado, se han citado genes asociados al parámetro pérdida por goteo y se identificaron tres genotipos en el gen *Dgat1* (Xu *et al*., 2009), el genotipo TT presentó menor pérdida de agua, mientras que en TC y CC las pérdidas fueron similares (67.1, 92.6 y 92.4 g kg^{-1}). Así mismo, el gen *Fabp4* está asociado al parámetro, con los genotipos AA, AG y GG (Xu *et al*., 2011). El genotipo AA presentó un menor porcentaje de pérdida por goteo (8.86, 9.48 y 9.39 %, respectivamente), aunque estadísticamente no hubo diferencias significativas (P<0.1). Así mismo, polimorfismos en el gen Calpaína Subunidad 1 (*Capns1*) han sido asociados a CRA, identificando cinco genotipos con diferencia en el porcentaje de pérdida de humedad (P<0.01); el genotipo B1B1 presentó 4.11% mientras que los genotipos A1A1, A1B1, A1C1 y B1C1 estuvieron en un rango de 2.23 a 3.30% (Grochowska *et al*., 2017). Además, dos genotipos en el gen de la Insulina como Factor de Crecimiento 1 (*Igf-1*) con efectos significativos sobre la pérdida por goteo han sido reportados, el genotipo homocigoto AA registró un 2.47% de pérdida, mientras que el heterocigoto AB un 3.33% (Grochowska *et al*., 2017). También el polimorfismo en el gen de la Miostatina (*Mstn*) ha sido asociado a este parámetro, obteniendo diferencias significativas (P<0.05) en el porcentaje de pérdida de agua, siendo el genotipo AA que registró un 2.5% mientras que AE un 3.5% (Grochowska *et al*., 2019).

Color.

El color de la carne es en gran medida el principal factor atractivo para el cliente, ya que perciben en este parámetro una señal de frescura y calidad, por lo que un color rojo en una carne ovina es preferible. El color de la carne cambia a medida que los pigmentos de mioglobina en la superficie de la carne entran en contacto con el oxígeno (Calnan *et al*., 2011), y van de deoxymioglobina (púrpura), oxymioglobina (rojo), hasta metamioglobina (marrón). Los valores de la Commission Internationale d'Eclairage (CIE) L* (negro-blanco), a*(rojo-verde) y b*(azul-amarillo) han sido utilizados para cuantificar el color de la carne, siendo utilizada una relación de reflectancia de la luz en las longitudes de onda de 630 nm y 580 nm para detectar cambios químicos en la carne debido a la oxigenación u oxidación de la mioglobina (Hunt *et al*., 1991).

Al respecto, se ha reportado diferencias significativas (P<0.05) entre los genotipos del gen Calpaina *Capns1* y las coordenadas de reflectancia L*, observando dos genotipos homocigotos A1A1 y B1B1 y tres heterocigotos A1B1, A1C1 y B1C1 en ovinos de la raza Merino (Grochowska *et al*., 2017), donde el genotipo B1B1 y A1C1 presentaron la menor y mayor unidades de luminosidad (38.05 y 41.13, respectivamente). Al igual que las calpaínas, el antagonista de esta enzima *Cast* es asociada al color, se han encontrado diferencias (P<0.05) para L* entre los genotipos MM y MN en ovinos Awassi (Jawasreh *et al*., 2017), el genotipo homocigoto presentó mayor luminosidad (37.60 y 32.47, respectivamente). Para el gen Estearoil-CoA Desaturasa (*Scd*) en ovinos iraníes, fueron identificados dos genotipos A y B, los cuales presentaron diferencias significativas para L* y a* (Aali *et al*., 2016), el genotipo B presentó mayor luminosidad L* (40.96 y 43.16, respectivamente), mientras que A presentó un mayor valor al color rojo a* (16.0 y 15.08, respectivamente).

En los ovinos de pelo, no existen investigaciones donde se evalúen los genes relacionados con características de la canal y la calidad de carne de importancia económica. Por lo que, evaluar genes relacionados a estos rasgos mediante técnicas moleculares, es de gran importancia para acelerar el mejoramiento genético de las razas de pelo.

Conclusión.

El CAR y GIR son índices que permiten identificar y seleccionar individuos eficientes en el uso del alimento y, en ovinos no se ha encontrado un efecto negativo sobre las características de la canal. Esta característica deseable (eficiencia) es de moderada heredabilidad, y está asociada a múltiples genes que pueden ser utilizados como marcadores moleculares para el mejoramiento genético. Por lo que, realizar trabajos de investigación que incluyan estos índices y el uso de técnicas moleculares en la selección y mejoramiento genético de ovinos de pelo, podría permitir predecir el comportamiento animal. Además, existen genes relacionados a rasgos de la canal y calidad de carne de importancia económica, que pueden ser incluidos en los programas de mejoramiento genético de estas razas. Con ello se podrá impulsar un mayor desarrollo de la ovinocultura, debido a que, individuos más eficientes tienen una menor ingesta sin afectar la tasa de crecimiento (CAR) o mayor ganancia de peso con ingestas similares de alimento (GIR), reduciendo los costos de producción e incrementando la rentabilidad de las unidades de producción. Además de producir alimentos de calidad que exige el mercado global y, contribuyendo en la reducción la huella ecológica de la ganadería.

CAPÍTULO 2. CAPÍTULO III. INTERPLAY AMONG FEED EFFICIENCY INDICES, PERFORMANCE, RUMEN FERMENTATION, CARCASS AND MEAT QUALITY IN TROPICAL PELIBUEY LAMBS

Highlights

- The RFI and RIG indices identified lambs with improved feed efficiency.
- Changes in RFI and RIG efficiencies did not affect lamb carcass traits.
- Low-RFI and high-RIG lambs have higher meat cooking loss.

Resumen.

Se evaluó la eficiencia alimenticia en treinta corderos Pelibuey no castrados, utilizando los índices consumo de alimento residual (CAR) y ganancia e ingesta residual (GIR). Los corderos fueron alimentados durante 92 días y luego sacrificados, con el objetivo de identificar la interrelación entre los índices de eficiencia alimenticia (FEI) y el comportamiento productivo, parámetros de fermentación ruminal, características de la canal y rasgos de calidad de la carne de los 15 corderos intermedios y más extremos para cada FEI. Los valores medios de las clases fueron -0,09, 0,00 y 0,09 kg MS/d para bajo, medio y alto CAR. Las medias de GIR fueron 2.6, -0.1 y -2.7, para alta, media y baja, respectivamente. Los corderos con alta-GIR mostraron una ganancia diaria promedio más alta y una mejor conversión alimenticia ($P \leq 0.05$). Los corderos con bajo-CAR y alta-GIR tuvieron valores más altos ($P < 0.05$) para pérdida por cocción en la carne. Los corderos eficientes tienen una eficiencia alimenticia mejorada, sin afectar el rasgo de la canal y la calidad de la carne (excepto por la pérdida de cocción).

Abstract.

Feed efficiency was measured in thirty Pelibuey noncastrated male lambs using the residual feed intake (RFI) and residual intake and gain (RIG). The lambs were fattened for 92 d and then slaughtered, with the aim of identifying the interplay between feed efficiency indices (FEIs) and performance, rumen fermentation parameters, carcass characteristics and meat quality traits from the 15 intermediate and most extreme lambs for each FEI. The mean values of the classes were -0.09, 0.00, and 0.09 kg DM/d for low, medium and high RFI, respectively. The RIG indicators were 2.6, -0.1, and -2.7, for high, medium and low, respectively. The lambs with high-RIG had a higher ($P \leq 0.05$) average daily gain and improved feed conversion. Lambs with low-RFI and high-RIG had higher ($P<0.05$) values of meat cooking loss. Efficient lambs had improved feed utilization without affecting the carcass characteristics or meat quality (except for cooking loss).

Key words: Hair sheep, residual feed intake, residual intake and gain, volatile fatty acid, lamb carcass.

Introduction.

In livestock meat production, the feed conversion ratio (FCR) has been used as an indicator of feed efficiency (Cantalapiedra-Hijar *et al*., 2018). However, this measure is questionable, because dry matter intake (DMI) is highly correlated with body size and the average daily gain (ADG) (Arthur & Herd, 2008). Therefore, using FCR as a selection criterion can help to detect animals with a high DMI, which results in higher production costs (Cantalapiedra-Hijar *et al*., 2018).

Various tools have been developed to predict and to select individuals with greater feed efficiency. The residual feed intake (RFI) is one of the most commonly used tools (Bezerra *et al*., 2013). The RFI is defined as the difference between the actual and expected feed intake for a given weight and ADG during a specific period (Koch *et al*., 1963; Arthur & Herd, 2008). Its objective is to identify the most feed-efficient animals and use them in breeding programs to reduce production costs per kg of live weight gains (Arthur & Herd, 2008). In addition, the residual gain (RG) has also been proposed as a measure of feed efficiency and is represented as the residuals from a multiple regression model between the ADG on both DMI and body weight (BW) (Koch *et al*., 1963). A feed efficiency indicator (FEI) called residual intake and gain (RIG) was proposed by Berry and Cowley (2012). This index conserves the characteristic of both RFI and RG independent of BW. However, RIG identifies animals with greater ADG and lower DMI than their contemporary classes.

Recently, it has been reported that efficient sheep require less DMI for growth. In this regard, Redden *et al*. (2014) reported a 9% lower DMI in low-RFI sheep, while Ellison *et al*. (2017)

reported a 30% lower DMI in low-RFI sheep. When using the RIG, FCR decreases in a range of 16 to 22% from inefficient to efficient animals (Lima *et al*., 2017; Carneiro *et al*., 2019, Nascimento *et al*., 2020). Furthermore, the classification of animals into groups of high, medium and low feed FEIs does not have any correlation with carcass characteristics (Carneiro *et al*., 2019; Nascimento *et al*., 2020). However, it has been reported that the concentration of volatile fatty acids (VFAs) in the rumen of lambs classified as low-RFI and fed a concentrated diet has a higher proportion of propionate (Ellison *et al*., 2017; Liang *et al*., 2017). Propionate is considered the main contributing substrate to the gluconeogenesis process, and is required as an energy source in protein synthesis (Allen, 2020).

In lambs, an association between FEI (RFI and RIG) and meat quality has been previously reported; for example, Montelli *et al*. (2021) reported higher values of color L* in high-RIG lambs. In Nellore cattle, Gomes *et al*. (2012) and Fidelis *et al*. (2017) reported no differences in meat quality (pH, color, shear force, drip loss, or cooking loss) between animals with low-RFI and high-RFI. On the other hand, Nascimento *et al*. (2016) reported higher values for shear force and lower values for color L* and intramuscular ether extract (EE) content in low-RFI animals. Only a lower intramuscular EE content was observed among efficient Nellore cattle using the RIG index (Nascimento *et al*., 2016). However, studies that relate the RFI and RIG to the quality of hair sheep meat, such as the Pelibuey breed, are scarce. Therefore, it is necessary to evaluate the relationship of the FEIs with meat quality in the hair sheep breeds that are usually raised in tropical regions.

In this context, the aim of this study was to determine the interplay between FEIs, performance, rumen fermentation parameters, carcass characteristics and meat quality in male Pelibuey lambs. This study will be of great value for regions where hair sheep are bred for meat production.

Materials and methods.

Pelibuey lambs used in this study were handled in compliance with the regulations for the use and care of animals intended for research and were approved by the Ethics Committee on Animal Use and Animal Care of the Colegio de Postgraduados (SUBINVTAB.CP. -105/18).

Location, management and experimental diet.

The experiment was carried out at the Southeastern Center for Ovine Integration (Centro de Integración Ovina del Sureste [CIOS]; 17° 78" N, 92° 96" W; 10 m altitude) located in Tabasco, Mexico. Lambs used in this study were contemporary animals managed under the standard prefattening management system. Thirty noncastrated male fattening Pelibuey lambs aged 123.03 ± 35.932 d (Mean ± SD) and 21.25 ± 4.608 kg (Mean ± SD) initial body weight (iBW) were used. The animals were kept in individual cages of 2 × 2 m in a raised-slatted floor cage system. The fattening period lasted for 92 d with an adaptation period of 15 d. Lambs were fed *ad libitum*, with the diet provided in two daily meals (0800 and 1500 h) and the daily refusals were kept at 10% of the amount of feed provided. The diet consisted of 80% concentrate and 20% forage on a dry matter (DM) basis (Table 2.1) and they had free access to water.

Table 2.1 Ingredients and composition of experimental diet.

Component	Content
Maize (g/kg DM)	528
Cynodon hay (g/kg DM)	200
Soybean meal (g/kg DM)	143
Molasses (g/kg DM)	60
Rice polishing (g/kg DM)	39
Urea (g/kg DM)	10
Vitamins and minerals* (g/kg DM)	20
Dry matter (g/kg as fed)	910
Organic matter (g/kg DM)	930
Crude protein (g/kg DM)	150
Ether extract (g/kg DM)	40
Neutral detergent fiber (g/kg DM)	420
Acid detergent fiber (g/kg DM)	170
Ash (g/kg DM)	70
Digestible energy (MJ/kg DM)	13.65
Metabolizable energy (MJ/kg DM)	11.3

Vitamin and mineral premix (in 1 kg): 40 g P, 60 g Ca, 20 g Mg, 0.0003 mg Se, 0.0005 mg Co, 0.1 mg Mn; 0.003 mg I, 0.1 mg Zn, 0.0002 mg Cu, 33.6 mg vitamin A, 0.55 mg vitamin D and 557.1 mg vitamin E.

The diet was formulated to meet energy (11 MJ/kg DM) and protein (85 g/d) requirements for growing sheep according to the equations of the Agriculture and Food Research Council (AFRC, 1993).

Samples of feed offered and individual orts were collected for five days in weeks 3, 6, 9, and 12, dried in a forced air oven at 55 °C for 72 h and then ground on a Wiley mill with a 1 mm screen to obtain composite samples for testing. The DM content (930.15), ash (942.05), crude protein (954.01) and ether extract (920.39) were determined according to the official methods of the Association of Official Analytical Chemists (AOAC, 1990). The NDF and ADF were determined using the methods described by Van Soest *et al*. (1991).

Performance.

The individual DMI, OM intake (OMI), CP intake (CPI) and NDF intake (NDFI) were calculated daily, obtained by the difference between the fed offered and the individual orts of DM. The iBW was determined after the adaptation period following 18 h of feed and water fasting. The BW was measured every week before feeding at 7 am. Likewise, the final BW (fBW) was measured on day 92 of the feed efficiency trial. The mean body weight (MBW) was obtained as the average of the BW records and the mean metabolic weight ($BW^{0.75}$) was calculated. The BW was modeled in time by simple linear regression to determine the average daily gain (ADG) using the PROC REG program from Statistical Analysis Software (Version 9.3, SAS Inst. Inc., Cary, NC). Before slaughter, the lambs were fasted for 18 h, and the slaughter BW (SBW) was recorded. The lambs were slaughtered according to the Mexican Standard NOM-033-SAG/ZOO-2014 for the humane slaughter of animals. After slaughtering, the hot carcass weight (HCW) was recorded, and the hot carcass yield (HCY) was calculated as the ratio between HCW and SBW.

Feed efficiency measurements.

The RFI and RG were modeled by multiple linear regression using the PROC REG program from Statistical Analysis Software (Version 9.3, SAS Inst. Inc., Cary, NC). The independent variables were ADG and $BW^{0.75}$ for RFI and DMI and $BW^{0.75}$ for RG (Koch *et al*., 1963), resulting in the equations described in Table 2.2.

Table 2.2 Regression equations to predict DMI and estimated ADG in growing Pelibuey sheep.

Equation	n	r^2	P-value
DMIe= -0.39(±0.13) + 2.03(±0.31) x ADG + 0.08(±0.01) x $BW^{0.75}$	30	0.86	<.001
ADGe= 0.19(±0.04) + 0.29(±0.05) x DMI - 0.02(±0.005) x $BW^{0.75}$	30	0.61	<.001

Subsequently, the equations were used to determine the expected DMI (DMIe) and expected ADG (ADGe). Residuals for RFI were calculated as the difference between DMI and DMIe. The residuals for RG were calculated as the difference between ADG and ADGe.

The values for RIG were calculated through the formula RIG = (RFI × -1) + RG described by Berry and Cowley (2012). The residuals of the RFI and RG indices were standardized using the STANDARD procedure of SAS (Version 9.3, SAS Inst. Inc., Cary, NC) with Mean = 0 and Standard deviation = one.

The lambs were classified as high-RFI (> 0.5 SD above the mean), medium-RFI (± 0.5 SD of the mean) and low-RFI (<0.5 SD below the mean). Among the 30 lambs, nine were classified as low-RFI, nine as high-RFI, and 12 as medium-RFI. For RIG, 11 were grouped in the low class, seven in the medium class, and 12 in the high class.

FCR was calculated as the ratio between DMI and ADG, while gross feed efficiency (GFE) was calculated as the ratio between ADG and DMI.

Rumen fermentation parameters.

On Day 45 of the fattening period, before feeding samples of rumen liquor were taken (20 mL) by esophageal tubing (Ramos-Morales *et al*., 2014). The Rumen liquor was filtered and deposited in Falcon® tubes, which contained 5 mL of 25% methaphosphoric acid (ratio 4:1). The samples were stored at -20 °C until analysis.

Samples of ruminal fluid from the five best-ranked lambs from the low-RFI, medium-RFI and high-RFI classes were used for VFA analysis, of which five were in the low-RIG class and five were in the high-RIG class. The analysis was performed as described by Gonzáles *et al*. (2009) with in a Hewlett Packard (6890, USA) gas chromatograph with an FID detector and G2613A automatic injector and an HP-FFAP capillary Column 19091 F-433 (Agilent, USA), 0.25 µm film, 30 m long and 0.25 mm diameter. Nitrogen was used as the carrier gas, H was used for combustion (33 mL min^{-1}), and air (330 mL min^{-1}) was used as an auxiliary gas flow (14 mL min^{-1}). The total run was 9.94 min for each analysis. The injector and detector temperatures were 230 and 240 °C, respectively. The oven conditions were ramp 1 (65 °C min^{-1}, 95 °C, for 0.15 min) and ramp 2

(15 °C min^{-1}, 145 °C, for 6 min). A standard (FAM6C; Supelco, USA) was used for volatile fatty acid detection.

The ammonia nitrogen (NH_3-N) concentration was determined following the phenol-hypochlorite method (McCullough, 1967). Lactic acid content was determined following the Taylor (1996) method.

Characteristics of the carcass measured by ultrasound.

Ultrasound measurements (USMs) were taken on Day 91 (before slaughter). The *longissimus thoracis* fat thickness (LTFT) and *longissimus thoracis* muscle area (LTMA) were determined using Chison® B-mode real-time ultrasound equipment (Medical Imaging Co., Ltd.; Wuxi, Jiangsu, China) with a 5-MHz linear probe. The lambs were shaved between the 12^{th} and 13^{th} thoracic vertebrae. Additionally, the maximum width of the *longissimus* muscle (A) and the maximum depth of the *longissimus* muscle (B) were measured as described by Morales-Martinez *et al*. (2020). The LTMA was then calculated as LTMA $cm^2 = ([A/2 \times B/2] \times \pi)$. The lambs were manually immobilized, and acoustic gel was used to create good contact between the probe and the skin of the animals. The pressure over the transducer head was kept to a minimum to avoid compression of the subcutaneous fat (Morales-Martinez *et al*., 2020). All measurements were taken on the right side of the lamb. After capturing the images, LTFT and LTMA were measured using electronic calipers as described by Morales-Martinez *et al*. (2020).

Physical chemical analysis in meat.

For meat quality analysis, a sample per lamb of the *longissimus thoracis* (LT) muscle from the left carcass was taken and kept at 4 °C until analysis. Physical and chemical analyses of the meat were carried out 24 h *postmortem*. All analyses of meat quality were performed on the 30 loins in triplicate, except for the cooking loss trial.

Meat pH was measured with a potentiometer Orion 3 start (Thermo Scientific, Massachussets, USA) according to the method established by Hernández-Hernández *et al*. (2009). Briefly, three samples of 10 g were homogenized in 100 mL of distilled water, the extract was filtered with cotton gauze, and the reading was carried out.

The color of the meat was determined using a Hunter Lab Mini Scan EZ colorimeter (Hunter Associates Laboratory, Reston, Virginia, USA). Meat slices from the LT muscle of approximately 2 cm were cut, and the freshly cut surface was exposed to air at room temperature for 30 min before color determination. Three measurements were taken at different positions along the muscle sample. The data were expressed according to the coordinates CIELAB, i.e., L*= 0 (black) to L*= 100 (white) represents luminosity, and -a* (green), + a* (redness), -b* (blue) and + b* (yellow), Hunterlab (1996).

The drip loss was determined according to the method established by Honikel (1998). Three samples of 50 g were hung with a nylon thread inside an airtight plastic bag to capture the exudate. The weight loss was calculated as the percentage relationship between the weight of the exudate after 24 h of refrigerated storage and the weight of the initial sample.

The cooking loss was determined in a sample per lamb at heights of the 11th and 13th thoracic vertebrae that were approximately 2.5 cm thick and baked at a temperature of approximately 170 °C. The internal temperature was monitored with individual thermometers placed in the geometric center of the sample. When the internal temperature reached 70 °C, the samples were removed from the oven and allowed to cool to room temperature. The loss was calculated as the percentage relationship between the weight of the raw and cooked sample.

Three 10 × 10 × 40 mm subsamples were taken from the cooked samples, parallel to the orientation of the muscle fibers to determine the shear force (SF). The SF was determined with a Shimadzu EZ-S 500 Newton (N) brand texture analyzer kit (Shimadzu Co., Japan), making a cut perpendicular to the orientation of the muscle fibers using a Warner Bratzler blade. The cutting speed was set at 60 mm/min and the data are expressed in N.

Analysis of the chemical composition of the LT muscle was performed on 30 lambs in triplicate, and the methodology for meat and meat products described by AOAC (1990) was used for analysis of the water content (9341.01), ash (924.05), crude protein (920.87) and intramuscular EE content (920.85).

Statistical analysis.

In a completely randomized design, data from the five worst-ranked lambs from the inefficient group, middle-ranked lambs from the intermediate group, and best-ranked lambs from the efficient group for both RFI and RIG were used and each animal represented an experimental unit. For the statistical analysis, the PROC GLM procedure of SAS (Version 9.3, SAS Inst. Inc., Cary, NC) was used, applying the statistical model described below: $Y_i = \mu + \beta_i + \varepsilon$

Where, Y_i is the response variable of the i-th animal, μ is the population mean, β_i is the effect of the RFI or RIG class (low, medium, high) of the i-th animal and, ε is the residual error.

Least squares means were calculated and compared using the Tukey test, and they were considered statistically significant when $P < 0.05$.

Results.

Performance.

In this study, the mean DMI was 1.22 ± 0.174 kg/d (mean ± SD) with a range between 0.89 and 1.68 kg/d, while the mean ADG was 0.23 ± 0.041 kg/d (mean ± SD), with a range between 0.14 and 0.32 kg/d. The iBW, fBW, MBW and $BW^{0.75}$ traits were not influenced by the RFI or by the RIG (Table 2.3). Low-RFI lambs consumed 95 g/d less feed, and the high-RFI lambs consumed 95 g/d more feed than expected ($P < 0.001$; Table 2.3). Low-RFI lambs had lower DMI, OMI, CPI and NDFI expressed in g/kg of MBW ($P < 0.05$) compared to high-RFI lambs. Likewise, the DMI percentage expressed as MBW and $BW^{0.75}$ was lower in the low-RFI group ($P < 0.001$ and $P < 0.01$, respectively) than in the high-RFI group. The DMI traits were not influenced by the RIG index (Table 2.3).

ADG, FCR, and GFE were not correlated with the RFI classifications. High-RIG lambs had a higher ($P = 0.05$) ADG than low-RIG lambs (Table 2.3), resulting in a difference of 49 g/d. In this sense, FCR showed a relationship with the RIG index ($P < 0.05$). High-RIG lambs required 1.07 kg less feed for each increase of one kg of body weight gain than low-RIG lambs (Table 2.3). Likewise, GFE showed a tendency ($P = 0.064$) toward improvement in the efficient lambs based on the RIG index. High-RIG lambs increased their body weight by 40 g per each kg of feed intake compared with the low-RIG lambs (Table 2.3).

Ruminal fermentation parameters.

The RFI index did not have a significant correlations ($P > 0.05$) with the relative proportions of acetate, propionate, and valerate (Table 2.4). Relative proportions of butyric, isobutyric and isovaleric were increased with low-RFI; however, no significant difference was observed between low-RFI and high-RFI lambs. The RIG index did not have a significant correlation ($P > 0.05$) with the rumen VFA relative proportions. The NH_3-N and lactic acid concentrations were not correlated ($P > 0.05$) with the FEI (Table 2.4).

Carcass characteristics.

HCY was unaffected ($P > 0.05$) by RFI or by RIG (Table 2.5). This result is explainable because the groups of lambs presented similar SBW and HCW in each FEI ($P > 0.05$). A similar situation was observed in the area of the LT muscle were no significant differences ($P > 0.05$) were observed between the lambs grouped by RFI or by RIG (Table 2.5), as the depth and width of the LT muscle did not differ ($P > 0.05$) between the animals classified by RFI or by RIG. Likewise, the subcutaneous fat thickness did not differ between the animals grouped by FEI evaluation.

Table 2.3 Mean and standard error of the mean (SEM) for performance traits of Pelibuey lambs classified as low, medium and high residual feed intake (RFI) and residual intake and gain (RIG).

Trait[1]	Residual feed intake					Residual intake and gain				
	Low	Medium	High	P-value	SEM	Low	Medium	High	P-value	SEM
DMI (kg/d)	1.20	1.31	1.36	0.498	0.050	1.30	1.18	1.28	0.488	0.042
DMI (g/kg/d of MBW)	34.1[b]	38.5[a]	40.2[a]	0.000	0.786	40.0	39.0	36.4	0.168	0.806
DMI (g/kg/d of $BW^{0.75}$)	83.1[b]	93.3[a]	96.0[a]	0.008	2.022	94.5	91.5	89.9	0.549	1.653
OMI (g/kg/d of MBW)	31.7[b]	35.9[a]	37.4[a]	0.000	0.734	37.2	36.3	33.8	0.167	0.758
CPI (g/kg/d of MBW)	5.4[b]	5.9[ab]	6.2[a]	0.023	0.125	6.3	6.0	5.8	0.174	0.105
NDFI (g/kg/d of MBW)	13.2[b]	15.5[a]	15.9[a]	<.001	0.346	15.6	15.4	13.9	0.129	0.379
DMI (% of MBW)	3.4[b]	3.9[a]	4.0[a]	<.001	0.079	4.0	3.9	3.6	0.165	0.081
DMI (% of $BW^{0.75}$)	8.3[b]	9.3[a]	9.6[a]	0.008	0.203	9.5	9.2	9.0	0.547	0.165
ADG (kg)	0.23	0.26	0.23	0.495	0.009	0.22[b]	0.24[ab]	0.27[a]	0.053	0.009
Initial BW (kg)	23.8	21.6	22.6	0.752	1.137	21.5	19.1	23.5	0.361	1.211
Final BW (kg)	46.7	46.2	45.2	0.910	1.390	43.3	41.6	47.2	0.222	1.340

MBW (kg)	32.3	33.9	33.9	0.885	1.237	32.4	30.3	35.3	0.257	1.223
MMBW$^{0.75}$ (kg)	14.5	14.0	14.0	0.863	0.382	13.7	12.9	14.3	0.377	0.397
FCR (kg of DMI/kg of ADG)	5.16	5.15	5.80	0.147	0.155	5.87[a]	5.01[ab]	4.80[b]	0.039	0.192
GFE (kg of ADG/kg of DMI)	0.19	0.19	0.17	0.190	0.005	0.17	0.20	0.21	0.064	0.007
RFI (kg/d)	-0.09[c]	0.00[b]	0.09[a]	<.001	0.022	0.09[a]	0.00[b]	-0.07[c]	<.001	0.021
RG (kg/d)	0.03[a]	0.01[a]	-0.03[b]	<0.001	0.007	-0.03[c]	0.00[b]	0.03[a]	<0.001	0.008
RIG (kg/d)	2.5[a]	0.4[b]	-2.6[c]	<0.001	0.616	-2.7[c]	-0.1[b]	2.6[a]	<0.001	0.612

[1] DMI= Dry matter intake, OMI= Organic matter intake, PCI= Protein crude intake, NDFI= Neutral detergent fiber intake, ADG= average daily gain, BW= Body weight, MBW= Mid-test body weight, BW$^{0.75}$= Metabolic body weight, FCR= Feed conversion ratio, GFE= Gross feed efficiency, RFI= Residual feed intake, RG= Residual gain, RIG= Residual intake and gain, [a, b, c] Different letters indicate significant differences ($P < 0.05$)

Table 2.4 Mean and standard error of the mean (SEM) for fermentative parameters of Pelibuey lambs classified as low, medium and high residual feed intake (RFI) and residual intake and gain (RIG).

Parameters	Residual feed intake					Residual intake and gain				
	Low	Medium	High	P-value	SEM	Low	Medium	High	P-value	SEM
Acetate	46.45	48.11	51.18	0.459	1.503	51.18		48.55	0.434	1.569
Propionate	27.56	25.80	28.01	0.777	1.258	28.01		26.17	0.248	0.762
Valerate	2.00	1.70	1.68	0.613	0.141	1.68		1.88	0.607	0.185
Butyrate	18.60[ab]	20.86[a]	14.90[b]	0.048	1.043	14.90		18.27	0.123	1.080
Isobutyrate	1.82[a]	1.37[b]	1.64[ab]	0.032	0.076	1.64		1.79	0.440	0.088
Isovalerate	3.57[a]	2.15[b]	2.58[ab]	0.011	0.218	2.58		3.33	0.160	0.260
NH_3-N (mg/dL)	14.24	15.02	15.37	0.931	1.166	13.70		11.32	0.423	1.385
Lactic acid (mmol/L)	0.32	0.36	0.36	0.696	0.023	0.36		0.28	0.185	0.030

[a, b, c] Different letters indicate significant differences ($P < 0.05$)

Table 2.5 Mean and standard error of the mean (SEM) for carcass trait of Pelibuey lambs classified as low, medium and high residual feed intake (RFI) and residual intake and gain (RIG).

Trait	Residual feed intake					Residual intake and gain				
	Low	Medium	High	P-value	SEM	Low	Medium	High	P-value	SEM
Slaughter body weight (kg)	42.81	42.63	41.32	0.874	1.194	40.25	38.35	43.66	0.142	1.115
Hot carcass weight (kg)	21.95	21.53	20.55	0.547	0.507	20.18	19.26	22.15	0.084	0.556
Hot carcass yield (%)	51.27	50.72	49.93	0.636	0.546	50.35	50.18	50.71	0.887	0.416
Thoracic fat thickness (mm)	2.90	2.82	3.12	0.662	0.013	2.92	2.50	2.90	0.408	0.014
Maximum thoracic depth (cm)	2.17	2.25	2.24	0.902	0.071	2.17	2.11	2.19	0.904	0.067
Maximum thoracic width (cm)	4.34	4.34	4.46	0.234	0.033	4.46	4.33	4.43	0.119	0.027
Longissimus thoracic area (cm^2)	7.42	7.68	7.86	0.836	0.278	7.62	7.20	7.62	0.754	0.249

Table 2.6 Mean and standard error of the mean (SEM) for chemical composition and meat quality of Pelibuey lambs classified as low, medium and high residual feed intake (RFI) and residual intake and gain (RIG).

Trait	Residual feed intake					Residual intake and gain				
	Low	Medium	High	P-value	SEM	Low	Medium	High	P-value	SEM
Ash (%)	1.13	1.13	1.09	0.242	0.011	1.09	1.14	1.11	0.098	0.010
Total protein content (%)	22.38	22.00	21.92	0.572	0.180	21.98	21.24	22.16	0.172	0.210
Water content (%)	73.15	73.50	72.98	0.748	0.268	73.15	73.63	73.23	0.739	0.256
Intramuscular EE content (%)	2.18	2.35	2.41	0.194	0.053	2.24	2.47	2.14	0.307	0.086
Muscle pH 24 h *post mortem*	5.78	5.91	5.97	0.755	0.098	5.98	5.78	5.90	0.674	0.088
L*, lightness	34.61	34.44	35.65	0.602	0.502	35.60	35.46	35.53	0.994	0.492
a*, redness	8.48	7.74	8.00	0.713	0.353	7.59	7.26	8.32	0.384	0.307
b*, yellowness	8.44	7.76	8.22	0.765	0.359	8.05	7.89	8.56	0.679	0.307
Warner Bratzler shear force (N)	74.15	67.32	62.38	0.830	7.380	56.92	74.45	61.87	0.475	5.776
Drip loss (%)	0.83	0.89	0.42	0.259	0.124	0.74	0.54	0.63	0.828	0.123
Cooking loss (%)	32.84[a]	28.48[ab]	25.95[b]	0.032	1.152	25.51	25.76	33.68	0.073	1.530

[a, b, c] Different letters indicate significant differences (P < 0.05)

Chemical composition and meat quality.

Intramuscular contents EE, total protein, ash and water contents of the meat did not differ between RFI classes or by RIG classes. There was a tendency (P =0.098) for a higher ash content from high-RIG lambs compared to low-RIG lambs (Table 2.6).

No differences (P> 0.05) were found for pH at 24 h, color (reflectance coordinates L*, a*, b*), shear force or drip loss of the meat from Pelibuey lambs from each FEI (Table 2.6). On the other hand, differences were observed in cooking loss (Table 2.6). The cooking loss from meat from low-RFI lambs was 4.36 and 6.89 percentage points higher than that from meat from medium and high-RFI lambs, respectively. For RIG, there was a tendency (P =0.073) for a higher cooking loss (Table 2.6). The cooking loss from meat from high-RIG lambs was 7.92 and 8.17 percentage points higher than medium and low-RIG lambs, respectively.

Discussion.

Performance.

Lambs with low-RFI consumed, 0.16 kg/d less DM which is equivalent to 11.76% less feed compared to high-RFI animals. A similar result was reported for ½ Dorper × ½ Santa Inês lambs, where efficient lambs consumed 0.17 and 0.19 kg/d less feed than inefficient lambs (Lima *et al*., 2017; Montelli *et al*., 2019). In previous studies of sheep, differences have been observed in the DMI between the RFI classes. The DMI is lower in animals with a low-RFI (Montelli *et al*., 2019; Zhang *et al*., 2019; Goldansaz *et al*., 2020). In this study, we did not observe differences in average

DMI; however, when standardizing the DMI, OMI, CPI and NDFI and expressing it in g/kg of MBW, significant differences were observed between the RFI classes (Table 2.3). On the other hand, not observing differences between ADG, initial BW, final BW, MBW and MMBW$^{0.75}$ between RFI classes is agreement with the definition of RFI proposed by Koch *et al*. (1963), since it is independent of the growth and productive level. In addition, some authors have reported that animals with low-RFI have a lower requirement of metabolizable energy for maintenance (Castro-Bulle *et al*., 2007; Gomes *et al*., 2012); therefore, they have a greater amount of energy for production.

Furthermore, animals with low-RFI have a higher efficiency in the generation of ATP from a given amount of substrate, due to a higher activity of the mitochondrial respiratory chain of complexes I, II, III, IV and V (Rajaei-Sharifabadi *et al*., 2012; Zamiri *et al*., 2017). This could explain the similar ADG with a lower feed intake among animals with low-RFI.

Likewise, it can explain a higher ADG in lambs with high-RIG when the DMI is similar between the RIG classes. This is in agreement with the results reported by Lima *et al*. (2017), Carneiro *et al*. (2019), and Montelli *et al*. (2019), who observed higher ADG among high-RIG lambs than low-RIG lambs (300 vs. 260 g/d, 310 vs. 260 g/d, 307 vs. 263 g/d, respectively). Furthermore, these authors observed that animals with high-RIG had an improved FCR, requiring one kg less feed for an increase of one kg of live weight compared to animals with low-RIG (4.28 vs. 5.32 kg, 3.91 vs. 4.99 kg, and 4.27 vs. 5.36 kg, respectively). In ½ Dorper × ½ Santa Inês lambs, Nascimento *et al*. (2020) reported that an increase in RIG efficiency improves FCR by 16%. In the present study, high-RIG animals improved FCR by 17%, which required an average of 1.04 kg less feed to increase the live weight by 1 kg compared to low-RIG lambs (4.80 vs. 5.87 kg, respectively). In other words, the high-RIG animals used less energy in the physiological processes that make up maintenance, and thus more energy was available for tissue deposition (Castro-Bulle *et al*., 2007; Gomes *et al*., 2012). Additionally, Montelli *et al*. (2019) and Nascimento *et al*. (2020) reported that better feed utilization by high-RIG lambs could be associated with lower rumination rates.

Rumen fermentation parameters.

The VFAs produced by ruminal fermentation constitute the main source of energy for ruminants (Allen, 2020). In sheep, it has been reported that molar proportions of propionate in the rumen are greater in animals with low-RFI than in those with high-RFI (Ellison *et al*., 2017; Liang *et al*., 2017), which suggests that the rumen microbiome of efficient lambs harbors specialized microbial species for propionate production that play an important role in increasing feed efficiency (Ellison *et al*., 2017). In fact, a recent study indicated that the rumen of efficient lambs harbors more abundant and diverse microbial communities than that of inefficient lambs and has a higher *Firmicutes*:*Bacteroidetes* ratio, which is related to energy metabolism (Zhang *et al*., 2021). However, in the present study, we did not observe differences in VFA concentrations between lambs with low-RFI and high-RFI, which suggests that the microbial communities are similar between efficient and inefficient lambs. When using the RIG index in a previous study, no differences were found in the concentration of VFAs (Giráldez *et al*., 2021a), which is consistent with the results of this study.

The results obtained for NH_3-N in the rumen when using both FEIs indicated that there were no differences between efficient and inefficient lambs. A possible explanation may be reflected in the fact that no difference was found in the average DMI. A similar concentration of NH_3-N in ruminal fluid using the RIG index was reported in Assaf lambs (Giráldez *et al*., 2021a), which is consistent with the results of this study. However, our results differ from those reported by Fitzsimons *et al*. (2014a) using the RFI index; they found that pregnant beef cows with low RFI fed grass silage had a lower concentration of NH3-N (10.2 mg/L) compared to those grouped in the medium and high RFI (18.3 and 20.7 mg/L, respectively).

In our study, lactic acid concentrations were low and similar between the animals classified by RFI and RIG, which suggests adequate feeding management for diet adaptation (Millen *et al*., 2016). A decrease in feed intake was not observed among the lambs. Lactic acidosis is a gastrointestinal and metabolic disorder, which is frequently observed in fattening cattle when the animals are subjected to diets high in starch or fast-fermenting carbohydrates (Millen *et al*., 2016).

Carcass characteristics.

No differences in carcass characteristics were observed between the RFI classes or by the RIG classes. Previous studies using the RFI index for the evaluation of carcass traits in crossbreeds of hair sheep (Dorper and Santa Inês, and Texel and Pantaneira) have reported no differences in carcass characteristics between RFI classes (Lima *et al*., 2017; Rocha *et al*., 2018). Likewise, a similar lack of differences was observed when the RIG index was used for crosses of the breeds Dorper and Santa Inês (Lima *et al*., 2017; Nascimento *et al*., 2020) and Texel and Pantaneira (Carneiro *et al*., 2019).

With regard to *longissimus* muscle characteristics, our study results agree with Nascimento *et al*. (2020) and Montelli *et al*. (2021), who reported that the lamb's *longissimus* muscle characteristics are not influenced by an increase in RIG efficiency. Therefore, it can be concluded that the FEI does not show a relationship with carcass characteristics, even when the low-RFI and high-RIG animals have a lower feed and energy intake.

Chemical composition of the meat.

The ash and total protein contents did not differ between FEI classes; this may be due to the proportion of protein and minerals in muscle tissue being relatively constant among different animal species (Fidelis *et al*., 2017). In Assaf lambs using the RIG index (Giráldez *et al*., 2021b) and Nellore bulls using the RFI index (Zorzi *et al*., 2013; Fidelis *et al*., 2017), no differences in ash and protein contents in *longissimus* muscle were observed, which agrees with our results. Furthermore, these authors observed similarities in the moisture content of meat between animals with low-RFI and high-RFI, which agrees with our results.

Although Nascimento *et al*. (2016) reported that efficient animals for the RFI and RIG indices have a lower intramuscular EE content than inefficient animals (2.84 vs. 3.22% and 2.85 vs. 3.21%, respectively), this finding partially explained by the lower feed and energy intake among efficient animals, since the difference in the energy retained in the body between efficient and inefficient animals is due to 5% feed intake and 95% heat production (Herd & Arthur, 2009). In this study, no differences were observed in intramuscular EE content between the RFI classes or the RIG classes. This result can be explained by the fact that the lambs had a similar DMI. This agrees with previous reports from Assaf lambs (Giráldez *et al*., 2021b) and Nellore cattle (Zorzi *et al*., 2013;

Fidelis *et al*., 2017); however, the authors did not report differences in EE content in the meat between efficient and inefficient animals. In general, the lambs presented a mean intramuscular EE content of 2.31 ± 0.303% DM (mean ± SD). This value is lower than that reported as acceptable by consumers, 5% EE (Hopkins *et al*., 2006). This may be explained by the fact that the study animals were growing, and intramuscular fat has been reported to increase with the animal's age (McPhee *et al*., 2008).

Meat quality.

In our study, there were no differences in pH 24 h *postmortem* between the groups classified by RFI or by RIG. Previous studies have not observed differences in the pH of meat from lambs (Giraldez *et al*., 2021b; Montelli *et al*., 2021) and Nellore cattle (Nascimento *et al*., 2016) classified by FEIs, which coincides with our study. Additionally, similar results in pH 24 h *postmortem* between RFI classes have been reported for Nellore cattle (Gomes *et al*., 2012; Zorzi *et al*., 2013; Fidelis *et al*., 2017). The mean pH value observed in this study was 5.81 ± 0.438 (mean ± SD), which is close to the recommended pH for good meat quality of small ruminants, which ranges from 5.5 to 5.8 (Almeida *et al*., 2017).

With regard to meat color in lambs, in our study, we did not observe differences in the L*, a*, or b* parameters between the classes for RFI or RIG. The factors that mainly influence meat color are the pH, the amount and chemical state of the muscle myoglobin, and the intramuscular fat (Corazzin *et al*., 2019). Therefore, a possible explanation for the results obtained for meat color is that we found no difference in pH or intramuscular EE content for either index. Montelli *et al*. (2021) reported lower values for L* in the high-RIG than in the low-RIG (33.13 vs. 35.28, respectively), which differs from the results obtained in this study. However, no difference in the color of lamb meat has been reported using the RFI index (Montelli *et al*., 2021) or the RIG index (Giráldez *et al*., 2021b), which agrees with the results obtained. Fresh lamb meat must have values greater than L* 34 and a* 9.5 to be considered acceptable (Khliji *et al*., 2010). In this sense, the mean values (mean ± SD) of color were L* 35.34 ± 1.904, a* 7.85 ± 1.187, and b* 8.28 ± 1.154, which are close to the acceptable meat parameters.

There are reports that the level of fatness in meat plays an important role in its tenderness. Therefore, for meat with a higher level of fat, less cutting force is needed compared to meat with a lower level of fat (Sañudo *et al*., 2000). In this sense, in our results we observed that the force required when cutting the cooked meat did not differ between the RFI classes or by RIG classes. A possible explanation for this result is that no differences were found in intramuscular EE content or pH 24 h *postmortem* between the classes. Similar results were reported in lambs, and it was observed that feed efficiency does not affect meat tenderness (Montelli *et al*., 2021); however, efficient lambs for the RIG index can produce meat that requires greater shear force 3 d after slaughter (Giráldez *et al*., 2021b). In Nellore cattle, the results are contradictory, since an effect of the RFI index on the shear force has been reported, indicating that animals with low-RFI have tougher meat (Zorzi *et al*., 2013; Nascimento *et al*. al., 2016). However, other authors have reported a similar shear force between RFI classes (Gomes *et al*., 2012; Fidelis *et al*., 2017).

Another parameter measured in meat was cooking loss at 24 h *postmortem*. The water content in meat is high (approximately 75%); of this, most of it is kept within the myofibrils, between the myofibrils, between the myofibrils and the cell membrane (sarcolemma), between the muscle cells and between the muscle bundles. A small proportion of water in the muscle also remains bound to proteins (Huff-Lonergan & Lonergan, 2005). The loss of water is related to the temperature used in the cooking process, inducing denaturation and contraction of the myofibrils and collagen proteins between 40 and 60 °C. Therefore, if water is lost, the meat will be more resistant and firmer (Suleman *et al*., 2020), affecting its quality. Animals with low-RFI and high-RIG presented greater loss, which suggests that efficient animals have greater contraction and rigidity of myofibrillar structures during the cooking process, causing greater water loss and lower meat quality (Giraldez *et al*., 2021b). This result agrees with that reported in Assaf lambs by Giráldez *et al*. (2021), who reported a greater cooking loss during the first measurement (0 d) in efficient lambs compared to inefficient lambs for RIG index (26.0 vs. 22.6%, respectively), but this differs from the reported results in Dorper × Santa Inês male lambs using the RFI and RIG indices (Montelli *et al*., 2021), with similar percentages of loss of cooking between low, medium and high classes.

Conclusions.

Overall, the efficient Pelibuey lambs had improved feed utilization without compromising their concentration of rumen VFAs. In this regard, low RFI lambs had lower feed intake without compromising their body weight gain. High RIG lambs had a higher average daily gain and improved feed conversion. Despite these relationships, the improvement of efficiency for both traits did not affect carcass characteristics. However, the meat quality is lower in efficient lambs, since there had greater cooking loss. The high cooking loss in meat from low-RFI and high-RIG lambs seems to be related to a high content of water bonded to protein in the fresh meat.

CAPÍTULO 3. IS VISCERAL ORGAN SIZE RELATED TO FEED EFFICIENCY IN TROPICAL HAIR SHEEP?

Resumen

El consumo de alimento residual (CAR) y ganancia e ingesta residual (GIR) son índices que miden la eficiencia alimenticia en rumiantes. Su aplicación se ha convertido en alternativas para mejorar la rentabilidad de los sistemas intensivos de producción ovina. Este estudio tuvo como objetivo evaluar los índices CAR y GIR y su relación con el tamaño de los órganos distintos a la canal y la grasa interna de los corderos. Se alimentaron treinta corderos machos no castrados durante 92 días. Posteriormente fueron sacrificados, y se pesaron los órganos distintos a la canal. Los corderos fueron clasificados en grupos de eficiencia baja, media y alta para el CAR y GIR. Los valores promedio para CAR fueron 0.07, 0.00 y -0.07 kg MS/d y los valores para GIR fueron 1.86, -0.20 y -1.91, para alto, medio y bajo, respectivamente. No se observaron diferencias ($P > 0.05$) en el tamaño de la canal, el tracto gastrointestinal y el hígado entre los corderos eficientes e ineficientes clasificados por CAR y por GIR. Los corderos eficientes (bajo-CAR y alta-GIR) tuvieron un mayor peso del corazón ($P \leq 0.05$). Se encontraron diferencias ($P < 0.01$) hacia mayor volumen de sangre y menor peso relativo en los depósitos de grasa omental y total en corderos con bajo-CAR. Aunque no se encontraron diferencias en el tamaño de los órganos con alta demanda energética para la absorción y metabolismo de nutrientes (hígado y tracto gastrointestinal) y la canal, los corderos clasificados como de bajo-CAR y alta-GIR tienen corazones más grandes, lo que podría estar relacionado con un rendimiento cardiovascular mejorado y mayor eficiencia alimenticia.

Palabras clave

Consumo de alimento residual, ganancia e ingesta residual, masa de órganos viscerales, grasa interna, corderos.

Abstract

The residual feed intake (RFI) and residual intake and gain (RIG) are indices that measure ruminant feed efficiency. Their application has become alternatives to improve the profitability of intensive lamb production systems. This study aimed to evaluate the accuracy of RFI and RIG to measure the non-carcass organ size and internal fat of lambs. Thirty non-castrated male lambs were fed for 92 days and slaughtered, and non-carcass organs were weighed. RFI and RIG were classified in low, medium and high efficiency groups, and correlated to carcass and non-carcass organ size. The average RFI values were 0.07, 0.00, and -0.07 kg DM/d and the RIG values were 1.86, -0.20, and -1.91, for high, medium and low, respectively. No differences ($P > 0.05$) were observed in the size of carcass, gastrointestinal tract, and liver between efficient and inefficient lambs classified by RFI and by RIG. The efficient lambs (low-RFI and high-RIG) had a higher heart weight ($P \leq 0.05$). Trends ($P < 0.01$) toward higher blood volume and lower relative weight in omental and total fat deposits were found in lambs with low RFI. Although no differences were found in the size of organs with high energy demand for the absorption and metabolism of nutrients (liver and gastrointestinal tract) and carcass, lambs classified as low-RFI and high-RIG had larger hearts, which could be related to improved cardiovascular performance and feed efficiency.

Keywords.

Residual feed intake, residual intake and gain, visceral organ mass, internal fat, lambs.

Introduction

The residual feed intake (RFI) and residual intake and gain (RIG) are two indices to measure the feed efficiency of livestock. They have become popular in recent decades because they are independent of body size and productivity (Koch *et al*. 1963; Berry and Crowley 2012). Both indices have become alternative measures applied to improve the profitability of intensive sheep meat production systems, where feed represents more than 70% of total production costs (Lima *et al*. 2017).

The RFI, proposed by Koch *et al*. (1963), is estimated by the difference between the actual feed intake and the expected feed intake for a given live weight and productive level during a period of time, and its objective is to identify the most efficient individuals in the use of feed, to enable selective breeding for genetic improvement (Arthur and Herd 2008). In turn, RIG aims to identify individuals with higher growth rates, to allow reducing confinement and slaughter times because commercial weights are reached at younger ages, in addition to having the advantage of improving feeding efficiency (Berry and Crowley 2012; Carneiro *et al*. 2019).

Among the biological mechanisms that contribute to the variation in feeding efficiency, non-carcass components have been reported to contribute 5% (Richardson and Herd 2004). The variation in the size and functionality of the liver and organs of the gastrointestinal tract is associated with a high metabolic cost, affecting the energy requirements of basal metabolism (Kenny *et al*. 2018). In addition, there is a relationship between feed intake and energy used to digest it, whereby higher intake is associated with greater the energy expenditure, due to an increase in the size of the digestive organs and the energy expended within the tissues of these organs (Herd and Arthur 2009). In this regard, it has been reported in lambs that efficient individuals (low RFI) present lower dry matter intake (DMI), with a difference of 160-190 g/d compared to inefficient ones (Lima *et al*. 2017; Zhang *et al*. 2017; Montelli *et al*. 2019), without affecting the daily live weight gain, because efficient lambs have a lower energy requirement for maintenance (Castro-Bulle *et al*. 2007; Gomes *et al*. 2012). Furthermore, a smaller DM intake is related to lower relative liver weight in lambs with low RFI (Zhang *et al*. 2017), and efficient lambs (low-RFI and high-RIG) tend to deposit less body fat (Carneiro *et al*. 2019; Montelli *et al*. 2021).

In Mexico, sheep production is one of the largest livestock activities, with an inventory of 8.7 million heads according to the most recent census (SIAP 2020), and Pelibuey is the most numerous tropical breed because of its maternal ability, high prolificacy, rusticity, resistance to parasites and good adaptation to tropical climates in Mexico (Chay-Canul *et al*. 2016). Nevertheless, there is little information about the efficiency of RFI and RIG as measures to guide herd management of tropical sheep breeds. It is important to validate new indices to select more efficient ewes and rams in order to reduce the production costs and select animals for breeding programs to improve genetic merit. Therefore, the aim of this study was to evaluate the RFI and RIG indices, and their relationship with non-carcass components, organ size, and internal fat in tropical Pelibuey lambs.

Materials and methods

The lambs included in this study were managed according to the guidelines for the use and care of animals destined for research in the tropics, and they study was approved by the Committee on the Use and Care of Animals of Colegio de Postgraduados, Mexico (SUBINVTAB.CP. -105/18).

Location, management and diet.

The study was carried out at the Centro Integral de Ovinos del Sureste (CIOS), located in Villahermosa, Tabasco, Mexico; with humid tropical climate. Thirty non-castrated male Pelibuey lambs with age of 123 ± 36 d and initial body weight (BWi) of 21 ± 5 kg were used. Lambs were housed in individual pens (2 × 2 m). The fattening period lasted 92 days after previous adaptation of 15 days. The diet provided contained 80% concentrated feed and 20% hay on a dry basis (Table 3.1). Fresh water was always available. The lambs were fed *ad libitum* at two times (0800 and 1500 h), and the feed was offered in excess to obtain a minimum feed rejected daily of 10%. The diet was formulated based on the energy (11 MJ / kg DM) and protein (85g / d) requirements for growing lambs according to the AFRC (1993).

Lamb performance.

The individual DMI was calculated daily by the difference between the feed offered and rejected on a dry basis. Body weight (BW) was recorded weekly, initial BW (BWi) was determined after the adaptation period, and final BW (BWf) was recorded 92 d after measuring feed efficiency. The mean body weight (MBW) was calculated once a week, from which the mean metabolic weight ($BW^{0.75}$) was calculated. The BW was modeled over time by linear regression to determine daily live weight gain (ADG) using the REG procedure (SAS 2012).

Table 3.1 Ingredients and composition of experimental diet.

Component	Content
Ingredients (g/kg DM)	
Maize	528
Cynodon hay	200
Soybean meal	143
Molasses	60
Rice polishing	39
Urea	10
Vitamins and minerals	20
Chemical composition	
Dry matter (g/kg as fed)	910
Organic matter (g/kg DM)	930
Crude protein (g/kg DM)	150
Ether extract (g/kg DM)	40
Neutral detergent fiber (g/kg DM)	420
Acid detergent fiber (g/kg DM)	170
Ash (g/kg DM)	70
Digestible energy (MJ/kg DM)	13.65
Metabolizable energy (MJ/kg DM)	11.3

Feed efficiency measures.

The residual feed intake (RFI) and residual gain (RG) indices were modeled by multiple linear regression using the REG procedure (SAS 2012). The independent variables were ADG, DMI, and $BW^{0.75}$ (Koch *et al*., 1963). Subsequently, the equation was used to determine the expected DMI (DMIe) and the expected ADG (ADGe). The residuals of the RFI index were calculated as the difference between the DMI and DMIe. Likewise, the residuals of the RG index were calculated as the difference between ADG and ADGe. Residual intake and gain (RIG) was calculated by the formula RIG = (-1 × RFI) + RG, as described by Berry and Crowley (2012). Previously, the residuals of the RFI and RG indices were standardized (Mean = 0 and Standard Error = 1) using the STANDARD routine (SAS 2012). Lambs were classified as low-RFI and low-RIG (< 0.5 SE below mean), medium-RFI and medium-RIG (± 0.5 SE from mean), and high-RFI and high-RIG (> 0.5 SE above mean).

Weight of organs.

Lambs were slaughtered according to the Mexican Standard NOM-033-SAG / ZOO-2014 after fasting for 18 h, and the slaughter weight (SBW) recorded. After slaughter, the blood was collected in plastic bags and the weight recorded. The weights of the visceral organs (spleen, heart, liver, lungs and trachea, pancreas, kidneys), gastrointestinal tract (empty stomach and intestines), fat deposits (total, mesenteric, omental and perirenal fat) and non-carcass external components (head, hooves, skin, and testicles) were immediately recorded. Empty body weight (EBW) was calculated by the difference between the SBW and the content of the gastrointestinal tract. The proportional weight of each organ, fat deposits and non-carcass external components was calculated in relation to EBW.

Statistical analysis.

A completely randomized design was used, where each lamb was an experimental unit. For the statistical analysis, the GLM procedure (SAS 2012) was used. Least mean squares were calculated and compared using the Tukey test at significance of $P < 0.05$.

Results

In this study, 30% of the lambs presented negative RFI values and were classified as low-RFI (efficient); 30% of lambs had positive RFI values and were grouped in the high-RFI class (inefficient); and the remaining 40% were classified as medium-RFI (Table 3.2). In the RIG index, 40% of the lambs had a positive value and were classified as high-RIG (efficient), 37% had negative RIG and were grouped in the low-RIG class (inefficient), and the remaining 23% were medium-RIG (Table 3.2). Low-RFI and high-RIG lambs had lower DMI, with differences of 0.146 and 0.117 kg DM/d compared to high-RFI and low-RIG lambs, respectively (Table 3.2). The EBW was not significant ($P > 0.05$) for both feed efficiency indices (RFI and RIG, Table 3.2).

Table 3.2 Least square means and standard error of the mean (SEM) for empty body weight (EBW) and feed efficiency traits of Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

Traits	Residual feed intake				Residual intake and gain				
	Low	Medium	High	P-Value	Low	Medium	High	P-Value	SEM
N	9	12	9		11	7	12		
EBW (kg)	36.58	36.30	35.21	0.753	35.07	35.36	37.38	0.347	0.732
RFI (kg DM/d)	-0.075[c]	0.002[b]	0.071[a]	<0.001	0.059[a]	0.006[b]	-0.058[c]	<0.001	0.012
RG (kg BW/d)	0.021[a]	0.001[b]	-0.023[c]	<0.001	-0.025[c]	-0.002[b]	0.024[a]	<0.001	0.004
RIG	1.990[a]	0.028[b]	-2.028[c]	<0.001	-1.910[c]	0.200[b]	1.868[a]	<0.001	0.344

RG= residual gain, [abc=] statistically significant differences.

The carcass yield was not significant (P> 0.05) for both feed efficiency indices (RFI and RIG, Table 3.3), but it had a significant effect on absolute (P ≤0.05) and relative (P ≤0.01 and P ≤0.05, respectively) heart weights. The efficient lambs (low-RFI and high-RIG) had heavier hearts than the inefficient lambs (high-RFI and low-RIG), without differences with the intermediate groups (except for relative weight in the RFI index, Table 3.3). Low-RFI and high-RIG lambs had hearts with greater relative weight (0.05 and 0.06%, respectively) compared to high-RFI and low-RIG lambs. The RIG index had a significant effect (P ≤0.05) on absolute intestine weight. Lambs with high RIG had 240 g heavier intestine weight than those with medium RIG, and non-significant differences of 190 g higher in the absolute weight of intestines in high-RIG lambs compared to low-RIG animals were found (Table 3.3). Except for the heart and intestines, no significant differences (P> 0.05) were found in the weights of the other visceral organs evaluated by both feed efficiency indices (Table 3.3). However, trends (P <0.1) to higher weight (absolute and relative) of blood were observed in lambs with low RFI compared to lambs with high RFI (Table 3.3).

The amounts of total, omental, perirenal and mesenteric visceral fat were not related to either feed efficiency index (Table 3.4). However, trends (P <0.1) to lower relative weight of total fat and omental visceral fat deposits were observed in lambs with low RFI compared to lambs with high RFI (Table 3.4).

Significant differences (P <0.05) were observed in absolute hoof weight for the RIG index (Table 3.5). Lambs classified with high-RIG had larger hoof weights than low-RIG lambs, and no difference was observed with medium-RIG lambs (Table 3.5). The weight of head, skin, and testicles did not differ (P> 0.05) according to both feed efficiency indices (Table 3.5).

Table 3.3 Least square means and standard error of the mean (SEM) for carcass and visceral organs size in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

Organs	Weight	Residual feed intake				Residual intake and gain				
		Low	Medium	High	P-Value	Low	Medium	High	P-Value	SEM
Carcass	Absolute, kg	20.69	20.58	19.96	0.715	19.93	20.11	21.07	0.372	0.368
	Relative, %	56.60	56.78	56.90	0.948	57.02	56.90	56.45	0.768	0.350
Heart	Absolute, kg	0.18[a]	0.16[ab]	0.15[b]	0.037	0.15[b]	0.16[ab]	0.18[a]	0.016	0.004
	Relative, %	0.49[a]	0.44[b]	0.43[b]	0.007	0.43[b]	0.44[ab]	0.48[a]	0.050	0.008
Blood	Absolute, kg	1.66	1.45	1.40	0.096	1.41	1.48	1.58	0.319	0.057
	Relative, %	4.53	4.02	3.97	0.084	4.02	4.18	4.27	0.651	0.112
Spleen	Absolute, kg	0.07	0.07	0.07	0.555	0.07	0.08	0.07	0.568	0.002
	Relative, %	0.20	0.21	0.20	0.725	0.21	0.22	0.19	0.227	0.006
Liver	Absolute, kg	0.69	0.73	0.67	0.265	0.68	0.71	0.72	0.475	0.015
	Relative, %	1.90	2.03	1.92	0.112	1.95	2.02	1.93	0.461	0.028
Lung and trachea	Absolute, kg	0.70	0.68	0.62	0.393	0.64	0.64	0.72	0.290	0.025
	Relative, %	1.91	1.88	1.77	0.599	1.83	1.80	1.91	0.738	0.057

Kidneys	Absolute, kg	0.11	0.12	0.11	0.219	0.11	0.12	0.12	0.643	0.002
	Relative, %	0.31	0.34	0.33	0.439	0.33	0.34	0.32	0.444	0.007
Stomach	Absolute, kg	1.00	1.01	0.98	0.791	0.98	0.97	1.04	0.416	0.022
	Relative, %	2.75	2.90	2.80	0.915	2.82	2.75	2.78	0.900	0.055
Intestine	Absolute, kg	1.13	0.96	0.98	0.163	0.95^{ab}	0.90^{b}	1.14^{a}	0.026	0.039
	Relative, %	3.08	2.64	2.79	0.153	2.72	2.58	3.05	0.118	0.094

^{ab}= statistically significant differences

Table 3.4 Least square means and standard error of the mean (SEM) for visceral fat depots weight in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

Fat Depot	Weight	Residual feed intake				Residual intake and gain				
		Low	Medium	High	P-Value	Low	Medium	High	P-Value	SEM
Total fat	Absolute, kg	2.71	3.32	3.10	0.264	3.10	3.15	3.00	0.930	0.154
	Relative, %	7.42	9.05	8.67	0.089	8.73	8.86	7.94	0.441	0.317
Omental	Absolute, kg	1.26	1.56	1.43	0.250	1.47	1.43	1.40	0.928	0.075
	Relative, %	3.44	4.26	4.02	0.096	4.14	4.03	3.70	0.480	0.160
Perirrenal	Absolute, kg	0.74	0.93	0.93	0.328	0.89	0.93	0.82	0.725	0.057
	Relative, %	2.04	2.52	2.62	0.200	2.52	2.61	2.17	0.374	0.135
Mesenteric	Absolute, kg	0.71	0.83	0.73	0.314	0.73	0.79	0.78	0.802	0.037
	Relative, %	1.94	2.18	2.04	0.128	2.07	2.22	2.07	0.666	0.071

Table 3.5 Least square means and standard error of the mean (SEM) for non-carcass external components size in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

Organs	Weight	Residual feed intake				Residual intake and gain				
		Low	Medium	High	P-Value	Low	Medium	High	P-Value	SEM
Hooves	Absolute, kg	1.03	0.95	0.96	0.214	0.93[b]	0.94[ab]	1.04[a]	0.045	0.021
	Relative, %	2.83	2.62	2.74	0.180	2.66	2.69	2.79	0.460	0.047
Skin	Absolute, kg	3.82	3.61	3.64	0.736	3.54	3.54	3.88	0.340	0.112
	Relative, %	10.50	9.90	10.26	0.384	10.03	9.99	10.39	0.544	0.160
Head	Absolute, kg	2.25	2.12	2.04	0.497	2.03	2.04	2.28	0.211	0.068
	Relative, %	6.14	5.82	5.73	0.341	5.73	5.76	6.11	0.316	0.115
Testicles	Absolute, kg	0.51	0.53	0.53	0.907	0.54	0.51	0.52	0.840	0.017
	Relative, %	1.40	1.46	1.50	0.548	1.52	1.44	1.40	0.361	0.034

[ab]= statistically significant differences

Discussion

As expected, the EBW and the size of the carcass did not differ when using both indices. This is explained because the residual feed intake (RFI) and residual intake and gain (RIG) are estimated independently of body size (Koch *et al*. 1963; Berry and Crowley 2012). In addition, efficient lambs may have lower energy requirements for maintenance (Castro-Bulle *et al*. 2007; Gomes *et al*. 2012), which allows more ingested nutrients to be distributed towards growth (Redden *et al*. 2013). The results reported by Montelli *et al*. (2021) showed that efficient lambs (low-RFI and high-RIG) have higher concentrations of the IGF-1 hormone compared to inefficient lambs (99.5 vs. 79.7 for RFI, and 88.8 vs. 73.9 for RIG). Therefore, efficient lambs have increasing muscle mass, since this hormone is involved in the regulation of metabolism and growth (Rechler and Nissley 1991). In this sense, efficient lambs (low-RFI and high-RIG) have more efficient metabolism, since they require less feed.

Regarding the size of visceral organs, our results showed that lambs with low RFI and high RIG had larger hearts, which could be due to greater cardiovascular efficiency and improved feed efficiency. The data reported by Munro *et al*. (2015) indicated greater relative weight of the right ventricle (22.0 vs. 21.3%, $P = 0.04$) and of the total ventricular weight (86.6 vs. 85.9%, $P = 0.05$) in relation to the whole heart weight, in cattle with low RFI. In addition, a positive correlation (0.29, $P = 0.005$) of thickness of the right ventricle with the RFI index was reported, indicating that cattle with high RFI have increased cardiovascular rate by spending less time resting, increasing DM intake with higher digestibility. The increased cardiovascular flow raises the heart rate and blood volume, and it is assumed that the pressure of the right atrium also increases, which can result in hypertrophy of the right ventricle. Therefore, cattle with high RFI have a higher workload of the right ventricle of the heart, and the selection of cattle with low RFI does not have a negative impact on cardiovascular structure and function (Munro *et al*. 2019). In this sense, a heavier heart and improved cardiovascular rate could explain why lambs with low RFI tend to have greater blood weight.

The difference in heart size found in this study differs from that reported in temperate and tropical sheep breeds, since no difference was reported in the heart weight among the classes using the RFI (Meyer *et al*. 2015; Zhang *et al*. 2017; Montelli *et al*. 2021), and RIG (Carneiro *et al*. 2019; Montelli *et al*. 2021). Likewise, it differs from that reported in cattle classified by RFI index (Basarad *et al*. 2003; Gomes *et al*. 2012; Fitzsimons *et al*. 2014b; Nascimento *et al*. 2016) and RIG index (Nascimento *et al*. 2016).

The size of the visceral organs and gastrointestinal tract has a high metabolic cost, so it is likely that the variation between animals in the size and functionality of these organs can impact the energy requirements (Fitzsimons *et al*. 2017). Although the gastrointestinal tract and liver account for a small proportion of body weight (6 to 13%), they utilize 38 to 50% of the maintenance energy required to absorb and metabolize digested nutrients (Burrin *et al*. 1990; Seal and Reynolds 1993). It has been reported that efficient beef cattle have smaller organs, such as liver (Basarad *et al*. 2003; Bonilha *et al*. 2009, Nascimento *et al*. 2016), gastrointestinal tract (Basarad *et al*. 2003; Bonilha *et al*. 2009) and empty reticulum-rumen (Fitszimons *et al*. 2014). Additionally, efficient individuals have lower DMI, so there is a relationship between feed intake and the energy used to digest it (the higher the intake, the greater the energy expenditure), due to an increase in size of the digestive organs and the energy expended within the tissues of these organs (Herd and Arthur 2009).

In this study we did not observe differences in liver and gastrointestinal tract weight between efficient and inefficient lambs. Although non-significant, differences in the absolute weight of intestines between low-RIG and high-RIG lambs were found. This difference was 190 g greater in efficient lambs, which suggests that greater gut mass improves nutrient absorption in high-RIG lambs, resulting in higher feed efficiency (Zhang *et al*. 2017). Montanholi *et al*. (2013) reported that bulls with low RFI had a greater amount of cell nuclei in the duodenum and ileum compared to high-RFI animals, indicating that efficient bulls have a more metabolically active small intestine, a trait that improves absorption of nutrients and energy efficiency.

On the other hand, Herd and Arthur (2009) reported a difference in the efficiency of the deposition of lean tissue (40-50%) and body fat (70-95%), and this variation in muscle was due to protein turnover. Lambs with low RFI tend to deposit less body fat (total and omental fat) compared to lambs with high RFI. These results can be explained because lambs with low RFI have lower feed intake (146 g DM/d less compared to high-RFI), and therefore lower energy intake. In this regard, Carneiro *et al*. (2019) reported that the lambs with high-RIG level had lower relative weight of total fat (4.95 vs. 5.91%), omental fat (1.89 vs. 2.30%) and mesenteric fat (1.20 vs. 1.48%) compared to lambs with low-RIG values. Montelli *et al*. (2021) also reported a trend towards lower omental fat deposition in efficient lambs (low-RFI and high-RIG animals) compared to inefficient lambs (0.748 vs. 0.876 kg for RFI, and 0.786 vs. 1.041 kg for RIG, respectively). However, several authors have reported that lambs classified by the RFI index do not differ in the amount of fat deposited (Meyer *et al*. 2015; Zhang *et al*. 2017; Rocha *et al*. 2018).

Regarding the non-carcass external components, high-RIG lambs showed higher hoof weight. This result agrees with that reported by Carneiro *et al*. (2019), who found higher relative weight of hooves in crossbred Texel x Pantaneira lambs classified by the RIG index. Likewise, no difference in hoof size has been reported using the RFI index (Zhang *et al*. 2017; Rocha *et al*. 2018), which agrees with our results.

Conclusions

Efficient lambs (low-RFI and high-RIG) had larger hearts, which could be related to improved cardiovascular performance and improved feed efficiency. In addition, low-RFI lambs tended to have higher blood volume and deposited less body fat. No differences in the non-carcass organ size with greater energy demand for the absorption and metabolism of nutrients were found (liver and gastrointestinal tract). More experimental studies are required to determine the relationship of feed efficiency with non-carcass organ size in tropical hair sheep. Finally, anatomy and physiology of the heart in tropical hair sheep are topics that need to be further evaluated.

CONCLUSIONES GENERALES

1. La metodología de los índices consumo de alimento residual y ganancia e ingesta residual evaluados en un sistema intensivo de producción ovina, permitió la identificación de corderos Pelibuey con un comportamiento eficiente en el uso del alimento.
2. En general, los corderos con bajo-CAR tienen un menor consumo de alimento sin comprometer la ganancia corporal. Los corderos con alta-GIR tienen una mayor GDP y mejor conversión alimenticia.
3. Los parámetros fermentativos ruminales (concentración de AGV´s, ácido láctico y NH3) no difieren entre corderos eficientes e ineficientes clasificados por ambos índices.
4. La eficiencia alimenticia en ambos índices no afecta las características de la canal y la calidad de la carne (excepto la perdida por cocción) de corderos Pelibuey. La alta pérdida por cocción en la carne de los corderos eficientes parece estar relacionado con un alto contenido de agua unida a la proteína en la carne fresca.
5. La eficiencia alimenticia no está relacionada con el tamaño de los órganos con mayor actividad metabólica (canal, hígado y TGI). Sin embargo, los corderos con bajo-CAR y alta-GIR tuvieron un corazón más grande, lo que podría estar relacionado con un mejor funcionamiento cardiovascular y una eficiencia alimenticia mejorada. Además, los corderos con bajo-CAR tendieron a tener mayor cantidad de sangre y depositar menos grasa corporal.

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