

Nutritional Imbalance and Energy Allocation in *Drosophila melanogaster*: A Theoretical Review of Excess Dietary Sugar

Sunita Devi¹

Research Scholar, Department of Zoology, Shri Jagadishprasad, Jhabarmal Tibrewala University, Jhunjhunu, Rajasthan, India

Dr. Imran Khan²

Assistant Professor, Department of Zoology, Shri Jagadishprasad, Jhabarmal Tibrewala University, Jhunjhunu, Rajasthan, India

Abstract:

This is a theoretical study that looks at the impact of excess dietary sugar on morphological, metabolic and reproductive characteristics of *Drosophila melanogaster*. The paper will discuss how hyperglycemia caused by high-sugar diets disruptions physiological balance. The discussion underscores the fact that metabolic dysfunction, which includes lipid accumulation, oxidative stress, and poor energy utilization, are the results of excess sugar. These metabolic imbalances are intimately connected to altered morphological development, diminished body size and distorted body composition. This also impacts the reproductive performance significantly, including reduced fecundity, delayed oocyte maturation, and decreased offspring viability. The paper also underlines how aging contributes to increasing such effects, leading to a faster physiological degeneration. The results highlight how closely diet, metabolism, and reproduction are related, which will provide a whole picture perspective on how high amounts of sugar consumption can affect the health and fitness of organisms.

Keywords: High-sugar diet, Hyperglycemia, Metabolic dysfunction, Energy homeostasis, Morphological traits, Reproductive fitness

1. Introduction

The growing use of sugar rich diets in the modern societies has become a critical issue owing to the widespread association with the metabolic disorders, such as obesity, insulin resistance, and hyperglycemia. Although the systemic effects of excessive sugar consumption have been well-known in humans, there is an increasing demand in understanding its wider physiological effects using model organisms. Of these, the genetic tractability, short life cycle, and metabolic pathways of *Drosophila melanogaster* have become a potent system of study of the biological effects of dietary sugar due to its genetic tractability, short life cycle, and conserved metabolic pathways [1], [2]. The organism gives a simplified but very informative platform to investigate the effects of nutritional excess on morphological development, metabolic regulation, and reproductive performance.

Carbohydrate metabolism has been core in the energy homeostasis in the living organism. In the normal dietary condition, the efficient use of glucose occurs via glycolysis and oxidative

phosphorylation, supplying energy to the body in sustaining growth, maintenance, and reproduction. Nonetheless, the processes may be disrupted by excess consumption of dietary sugar, resulting in hyperglycemia and metabolic overload. In *Drosophila melanogaster*, diets high in sugar have been found to cause physiological changes which closely resemble human metabolic disorders, such as elevated hemolymph glucose levels and increased lipid storage, and impaired insulin signaling [3], [4]. These metabolic impairments may be followed by oxidative stress and loss of lifespan, indicating the adverse consequences of chronic hyperglycemia on organism health [5].

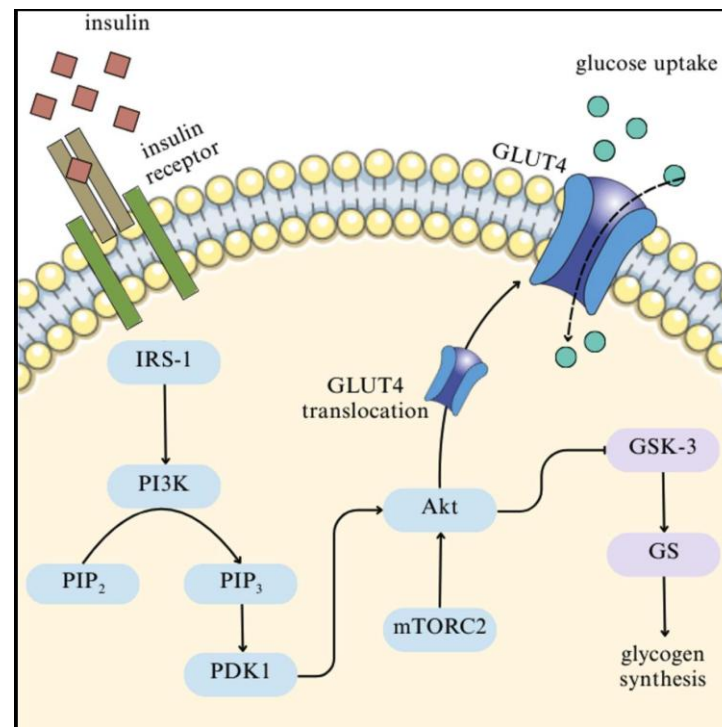


Figure 1: Metabolic pathways and physiological consequences of excess dietary sugar and hyperglycemia [7]

Morphological characteristics like body size, weight, and structural size are significant markers of developmental well-being and physiological performance. The nutritional status is instrumental in the determination of these characteristics, as it has a direct effect on the growth pattern and tissue development. High dietary sugar may result in abnormal morphological consequence through changing the distribution of energy and metabolic equilibrium. Research has shown that increases in lipid accumulation with high-sugar diets are accompanied by disproportionate changes in body size, resulting in changes in body composition and physical performance [6], [7]. This lack of balance is the inefficient use of energy sources and it is the multifaceted relations between the diet and morphological development.

Drosophila melanogaster regulates metabolism by conserved signaling pathways, such as the insulin and target of rapamycin (TOR) pathways, which mediate nutrient sensing and energy use. These pathways are important in the maintenance of metabolic homeostasis by regulating such

processes as glucose uptake, lipid storage, and protein synthesis. In the case where there is excess consumption of sugar, such regulatory mechanisms are broken, which, in turn, results in disrupted metabolism efficiency and storage of energy in the form of lipids [8], [9]. The metabolic imbalance that results does not only impact the availability of energy, but also leads to cellular stress and lack of physiological resilience.

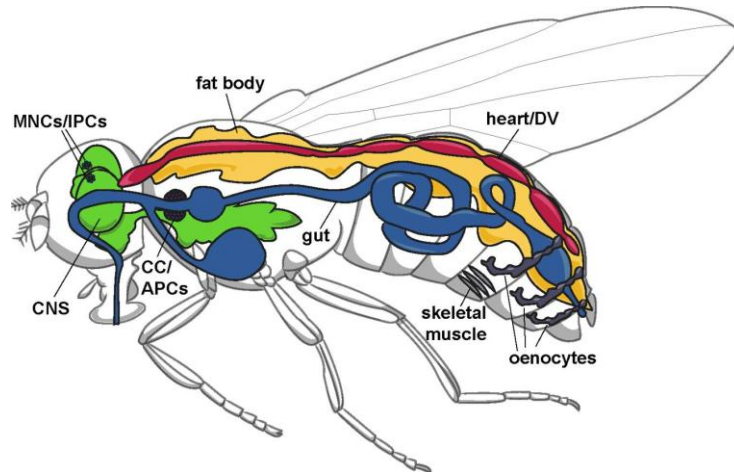


Figure 2: Morphological structure and reproductive system of *Drosophila melanogaster*

Reproductive fitness is an essential quality of biological prosperity and is extremely delicate to nutritional and metabolic circumstances. The reproductive aspects of fecundity, ovariole count and offspring fitness of *Drosophila melanogaster* are conditional on the availability of energy and nutrients. A high amount of sugar in the diet has been found to adversely influence these characteristics by changing energy distribution and hormonal balance. In hyperglycemic states, energy may be diverted away both at the reproductive processes and at the development of the oocyte, towards processes of either maintenance or responses to stress [6], [10]. These effects underline the interconnection of metabolic and reproductive systems, and the importance of balanced nutrition to achieve optimal reproductive performance.

Another important factor influencing the effects of dietary sugar is aging. The older the organisms get, the less they are able to control their metabolism and achieve physiological homeostasis. The processes related to aging in *Drosophila melanogaster* include reduced metabolic efficiency, increased oxidative stress, and decreased reproductive capacity. These age-related changes are frequently compounded by high-sugar dietary conditions, which not only intensify the process of age-associated physiological decline, but also result in the shortening of life expectancy [5], [11]. The interplay of diet and aging highlights the need to take into consideration the time-dependent aspects when examining the impact of nutritional stress.

The energy allocation concept is an appropriate framework used in comprehending the way organisms react to a surplus of dietary sugar. In the normal condition, growth, maintenance, and reproduction are the three factors that share the energy. Nevertheless, when conditions of metabolic stress, such as hyperglycemia, are present a higher proportion of energy can be used to maintain basic physiological functions and to cope with stress, leaving less energy available to

provide growth and reproduction. This energy redistribution may lead to less morphological growth and reproductive performance, which in turn may impact on overall fitness [7], [10].

Although the metabolism effects of high-sugar diets have been widely studied, there is still a need to conduct integrated studies that will examine the cumulative effect of dietary sugar on morphological, metabolic, and reproductive aspects. The available research has been done individually on different aspects of physiology without taking into account the fact that they are interconnected. The full picture needs to be taken in order to gain a complete understanding of how excess dietary sugar affects the health and fitness of organisms. The current research fills this gap by exploring the interactive effects of high sugar diets on multiple physiological parameters in *Drosophila melanogaster*, which offers a comprehensive view of the stresses caused by high sugar diets.

2. Theoretical Framework

The theoretical foundation of the research is in the combination of the theory of nutritional ecology, metabolic regulation theory, life-history theory and stress physiology. The combined impact on the organismal structure, energy interchange and reproductive fitness by the aggregate effect of these structures is explicated.

The central key to this is that the principle of energy homeostasis states that organisms balance the energy intakes, storage, and expenditure. In normal dietary states, carbohydrate sources of energy are effectively utilized in the growth, maintenance, and reproduction. Nevertheless, when you eat too much sugar, the balance is lost and this causes metabolic overload. This imbalance leads to hyperglycemia, lipid storage and distorted metabolic signaling pathways, especially the insulin and TOR signaling pathways.

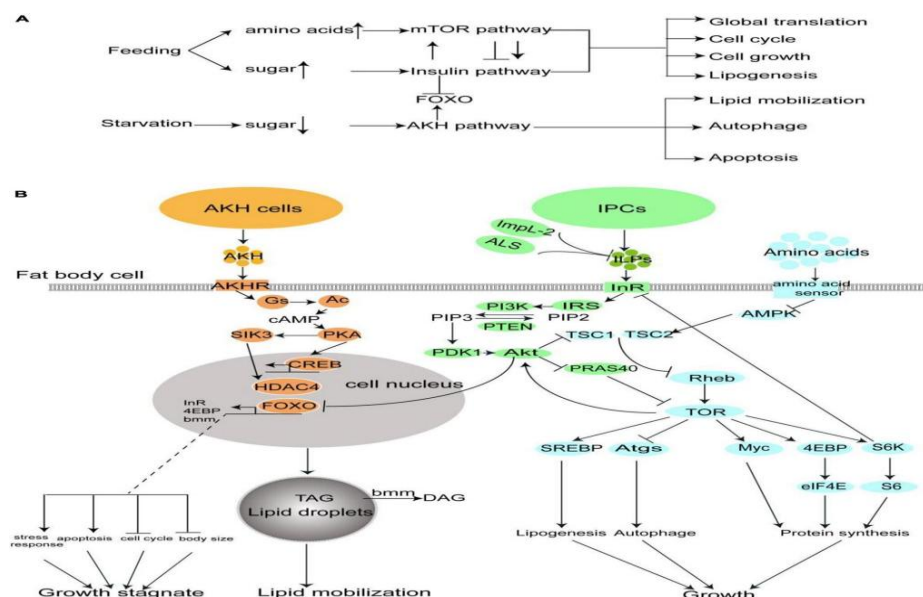


Figure 3: Theoretical framework integrating energy balance, metabolic stress, and life-history trade-offs [4]

The theory of life-history also describes how living organisms distribute scarce resources to competing physiological activities. When stressed by hyperglycemia, energy is allocated to survive and maintain, frequently at the cost of growth and reproduction. Such trade-off mechanism may be critical towards explaining the decreases in morphological growth and reproductive yield that may be observed under high-sugar conditions.

2. Literature Review

The effects of dietary composition on organism physiology has been the subject of a large amount of study in recent years, especially in relation to the growing prevalence of metabolic disorders linked to excessive sugar intake. There has been a strong correlation between high-sugar diets and conditions including obesity, hyperglycemia, insulin resistance and decreased physiological efficiency. Although much of the research has concentrated on the human health, model organisms such as *Drosophila melanogaster* have helped to understand the biological processes behind these effects. *Drosophila* has become a generally accepted model to study diet induced alterations in morphology, metabolism and reproduction.

Among the key conclusions of the literature is the fact that overabundance of dietary sugar causes serious metabolic disorders. Experiments have shown that hyperglycemic states develop in *Drosophila melanogaster* subjected to high-sugar diets, which are characterized by elevated hemolymph glucose levels and insulin resistance. These metabolic alterations are in close association with those experienced in humans who have metabolic syndrome. According to Palanker Musselman et al. (2011), high-sugar diets induce insulin resistance and fat buildup in flies, which is quite similar to the reaction of mammals to high-sugar diets. This observation has been reinforced by later studies that have shown that long-term exposure to high sugar results in diminished metabolic efficiency and augmented oxidative strain, eventually influencing the well-being and lifespan of living organisms.

Besides the effects of sugar on the metabolic processes, the morphological characteristics are affected profoundly by the dietary sugar. Nutrient availability and energy allocation are of great importance in morphological development in *Drosophila melanogaster*. In the normal conditions, nutrients are optimally used to sustain growth and structural development. But too much sugar obstructs such balance by favoring lipid build-up, as opposed to structural development. Lushchak et al. (2014) noted that a high intake of carbohydrates results in an increase in body weight without corresponding increase in body size, which leads to changes in body composition. This disbalance is indicative of inefficient energy use and is indicative of the value of nutrient quality in defining morphological results. Klepsatel et al. (2020) also highlighted the role of nutrition during developmental periods to influence adult morphological characteristics, implying that the nutritional exposure during developmental stages has long-term effects.

Close association of metabolic regulation is related to energy balance and nutrient utilization signaling pathways. In *Drosophila melanogaster*, the insulin and target of rapamycin (TOR) pathways play a crucial role in metabolic homeostasis. These pathways control the processes of glucose uptake, protein synthesis, and lipid metabolism. These pathways have been demonstrated

to be disrupted by high-sugar diets resulting in the impairment of glucose metabolism and excessive storage of lipids. Shin et al. (2011) showed that the gut microbiota has a role in regulating these metabolic pathways and, thus, changes in microbial composition that are induced by diet can alter host metabolism. The impairment of these regulatory functions leads to the decreased efficiency of metabolic processes and physiological stress.

Figure 4 shows a published photographic example of monitoring food ingestion, relevant to the distinction between nutrient intake and utilization. (Eickelberg et al., 2022).



Figure 4. Visible uptake of dyed food by adult *Drosophila*

Note. The blue abdominal coloration marks ingested Brilliant Blue FCF dye. This is a feeding-assay photograph, not a high-sugar phenotype or evidence of tissue damage.

Source: Reproduced from Figure 4 of Eickelberg et al., 2022. <https://doi.org/10.3390/biom12020221>. © the authors; CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

The other key element of the literature is the mediation of the effects of excessive dietary sugar by oxidative stress. The hyperglycemia is linked to the excessive production of reactive oxygen species (ROS) which can damage the cellular components like proteins, lipids and DNA. This oxidative injury adds to a lowering of cellular performance and hastens the aging procedure. Van Dam et al. (2020) found that flies that are exposed to high-sugar diets experience elevated

oxidative stress and reduced lifespan, which highlights the long-term effects of metabolic imbalance. Over time, accumulation of oxidative damage only increases adverse effects of dietary sugar on physiological systems.

The intake of dietary sugars also has significant impacts on reproductive performance. Reproduction is an energy-demanding process, which needs a balanced intake of nutrients. In high sugar consumption conditions, the energy distribution will be focused on maintaining and responding to stress, with less energy being allocated to reproduction. It was found that high-sugar diets in *Drosophila melanogaster* cause a reduction in fecundity, which is an indicator of reproductive output (Lushchak et al. 2014). Likewise, Klepsatel and colleagues (2020) showed that dietary composition impacts reproductive characteristics including egg production and viability of offspring. These results imply that metabolic wellbeing is strongly associated with sexual achievement.

Hormonal regulation also plays a role in the interaction between metabolism and reproduction. Insulin-like peptides, and juvenile hormone are hormones that are critical in the coordination of metabolic and reproductive processes. Interruption in these hormonal pathways in hyperglycemia conditions can cause disruption in oogenesis and low reproductive efficiency. This emphasizes the interrelation of physiological systems and the significance of maintaining metabolic balance in order to have optimal reproductive functioning.

3. Morphological Implications of Excess Dietary Sugar

Morphological traits are the outward signs of the internal physiological processes and health in general. Body size, weight, and length of the thorax are directly affected by nutritional status in *Drosophila melanogaster*. An imbalance between anabolic and catabolic mechanisms causes deviations in normal growth patterns in case of excess dietary sugar.

In hyperglycemic states, the excess glucose is metabolized to lipids via de novo lipogenesis. Although this is associated with more body weight, it is not related to proportional structural developments. As a result, flies are found to have an increase in body mass and a decrease in body size which lead to abnormal body composition. This situation represents an occurrence of so-called metabolic obesity whereby the energy is not used in growth but is stored inefficiently.

In addition, the protein production is compromised by high-sugar diets and is critical to tissue development. The low supply of proteins causes a decrease in the structural integrity and the deterioration of morphological characteristics. These effects increase with age, and in old age, when efficiency of growth is even lower, they become more pronounced.

Theoretical models imply that morphological development is closely associated with energy allocation. As surplus energy is redirected in the storage process instead of making structural developments, morphological anomalies arise. This disequilibrium supports the significance of the quality of nutrients, rather than their quantity, in shaping the developmental outcomes.

4. Metabolic Consequences of Hyperglycemic Stress

The control of metabolism is the main focus in comprehending the physiological effects of excessive dietary sugar. Metabolic processes in *Drosophila melanogaster* are regulated by

conserved pathways that govern glucose metabolism, lipid storage and energy utilization. The diets high in sugar interfere with these pathways resulting to a state of metabolic dysregulation. The hyperglycemia leads to a high amount of glucose in circulation that may exceed the cellular metabolic rate. Excess glucose is converted to lipids as a compensatory mechanism, with a resultant fat accumulation. This process, in addition to adding body mass, also leads to metabolic inefficiency. Oxidative stress is another important outcome and is defined by excessive production of reactive oxygen species (ROS). These are molecules that lead to cellular damage through oxidation of proteins, lipids, and DNA. Oxidative damage builds up, impairs cellular activity and speeds up aging. Moreover, the hyperglycemic conditions result in the impairment of insulin signaling. The resistance of insulin decreases the capacity of cells to absorb glucose, thus worsening hyperglycemia. This forms a feedback mechanism in which metabolic impairment feeds on itself. There is also a dropped efficiency in energy conversion as the body becomes less efficient in converting nutrients into useful energy. This lack of efficiency results in greater energy usage in the maintenance processes, and leaves less energy to use in the growth and reproduction processes.

Figure 5 shows published apparatus used to study respiration as a component of metabolic phenotyping. (Eickelberg et al., 2022).

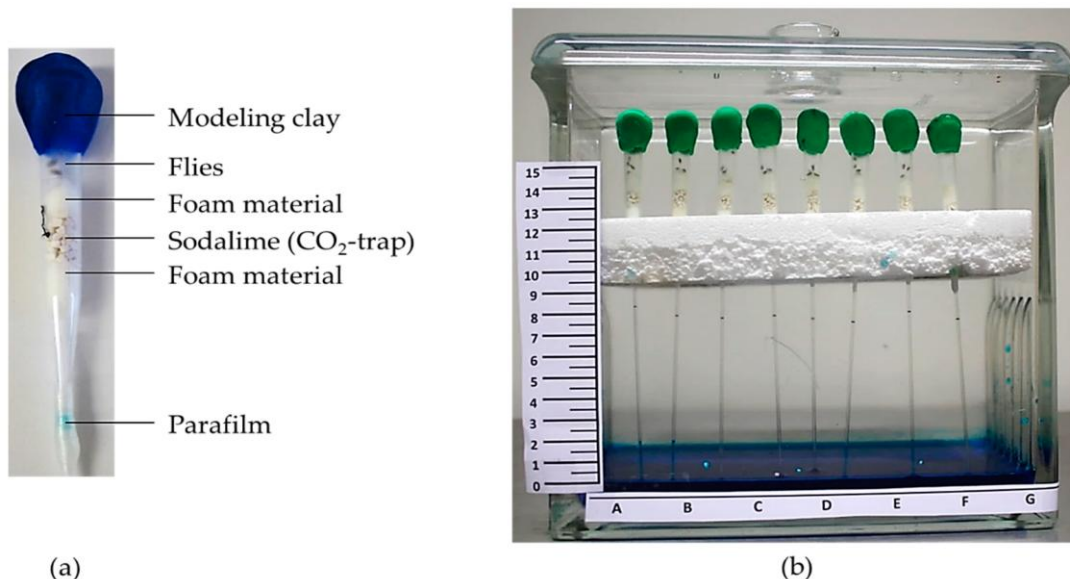


Figure 5. Respirometer apparatus for *Drosophila* metabolic assessment

Note. Photographs show an individual chamber and assembled respirometers. They provide methodological context for this theoretical discussion and do not indicate that this apparatus was used in the present paper.

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5. Reproductive Consequences of Excess Sugar Intake

Metabolic health and availability of energy are very dependent on reproductive fitness. Fecundity, ovariole number and offspring viability are all directly affected by nutritional condition in *Drosophila melanogaster*.

High dietary sugar causes a decline in reproductive output in a number of ways. To begin with, there is a redistribution of energy between reproduction and maintenance and stress response. This will lead to a less amount of resources in producing eggs as well as developing them.

Second, the hormonal balance is disturbed. The juvenile hormone and ecdysteroids are essential hormones in oogenesis. Hyperglycemia disrupts these hormonal pathways resulting in failure by oocytes to mature and poor reproductive performance.

Third, metabolic stress results in the poor quality of gametes. The oxidative damage may reduce the viability of eggs, thus decreasing the survival of offspring. Also, the build of lipid in reproductive tissues can disrupt normal reproductive functioning.

Theoretically, these effects can be attributed to life-history trade-offs, whereby organisms focus on their survival rather than on reproduction under stressful conditions. This adaptive mechanism makes survival in the short-term but decreases reproductive success in the long-term.

6. Discussion

The current theoretical studies offer a thorough insight into the effects of excess dietary sugar on morphological, metabolic and reproductive characteristics of *Drosophila melanogaster*. The overall findings point to the suggestion that hyperglycemia caused by high-sugar diets is a central physiological stressor, which disrupts many biological systems at the same time. These outcomes are incorporated into the wider theoretical frameworks of energy homeostasis, metabolic regulation, as well as life-history trade-offs.

Among the most important observations is the imbalance of metabolism in a situation of overconsumption of sugar. Hyperglycemia causes too high levels of glucose that the energy need of the organism cannot process, and thus, energy is not utilized efficiently. Rather than undergoing instant physiological activities, the surplus glucose is transformed into lipids, which is the cause of the abnormal accumulation of fat. This process corresponds to a change in the efficient energy metabolism to storage-dominated pathways which undermine the overall metabolic health. Although the accumulation of lipids seems to cause an increase in the energy reserves of the body, it ultimately results in metabolic overload and decreased physiological efficiency of the body. This may help give credence to earlier theoretical models which attribute metabolic dysregulation to be a major effect of nutritional excess.

The morphological consequences of this metabolic imbalance, are also of considerable importance. The paper emphasizes that there is no proportional structural development in relation to increased body weight under conditions of high sugar. Rather, flies have smaller body size and changed body composition, suggesting a decoupling between the energy intake and the growth processes. This implies that morphological development does not solely rely on the caloric intake but is greatly influenced by the quality and use of nutrients. The results support the idea that the

undue presence of sugar interferes with the regular developmental trajectories of the organism that may result in the structural inefficiencies that can cause the inability to move, survive, and be fit. The other important point that is addressed is the mediation of the effects of hyperglycemia by oxidative stress. Excessive production of reactive oxygen species (ROS) under high-sugar conditions causes cellular damage, which is manifested by damage to proteins, lipids, and DNA. This oxidative damage does not only diminish the functioning of cells, but also hastens the process of ageing. The accumulative effect of oxidative stress leads to the reduction in the efficiency of metabolism and the physiological resistance observed at advanced stages of life. These results are in agreement with the theories of stress physiology that emphasize the effects of chronic stressors on biological aging acceleration and lifespan reduction.

Reproductive performance is one of the most sensitive measures of physiological stress. The discussion provides evidence that excess dietary sugar can dramatically decrease fecundity, delay the maturation of the oocytes and decrease the viability of the offspring. The mentioned effects can be explained in the frames of energy allocation theory, which states that, under stressful conditions, organisms tend to allocate energy to survival rather than reproduction. The change in the distribution of energy to maintenance and stress response mechanisms leads to less investment in reproductive processes. The adaptive mechanisms used by organisms to deal with stresses in the environment are the focus of this trade-off, but at the expense of lowering reproductive success. The interplay between metabolic and reproductive systems further emphasize the complexity of physiological regulation. Reproduction depends on energy supplied by metabolic pathways, and reproductive processes result in the extra demands of metabolic resources. This coordination is disrupted in hyperglycemic conditions by disruption of the metabolic signaling pathways, specifically insulin and TOR pathways. These effects are further aggravated by hormonal imbalances that bring about a decrease in reproductive efficiency. This level of interconnectedness supports the idea that these physiological systems cannot be studied in the context of the entire system and that instead of studying them as isolated components of the system, one should study them as parts of the system.

Effects that are age-dependent are critical in enhancing the effects of excess dietary sugar. *Drosophila melanogaster* becomes more vulnerable to adverse impacts of hyperglycemia as it ages and has lost its ability to effectively regulate metabolism. The discussion points out that aging contributes to worsening metabolic inefficiency, oxidative stress, and further deteriorate reproductive capacity. This diet-age interaction supports the idea of cumulative physiological stress whereby continued exposure to unfavorable conditions results in progressive deterioration of health and functioning. The results indicate that the time and length of dietary exposure are important determinants in the determination of physiological outcomes.

The physiological health concept is integrated, which offers a holistic view of the results. When morphological, metabolic, and reproductive characteristics are taken into account altogether, one can clearly see that excess dietary sugar has a systemic effect on organismal fitness. The reduced integrated physiological index when in high-sugar conditions are a cumulative effect of

dysfunction in metabolism, structural pathophysiology, and reproductive senescence. This holistic method provides a better estimate of organism health than does single measurements.

In a more general sense, the study is a part of the knowledge on the way dietary factors interact with the biological systems. The results emphasize that the impact of high sugar intake is not confined to metabolic imbalances but also to the structural development and reproductive success. This highlights the fact that balanced nutrition plays a crucial role in ensuring physiological homeostasis. The *Drosophila melanogaster* model organism has proven useful in providing insights that may be applicable in a higher organism, such as humans, particularly when it comes to the diet-induced metabolic disorders.

7. Conclusion

The experiment shows that dietary sugar as excess is an important stressor in *Drosophila melanogaster* that disrupts various physiological systems. Hyperglycemia causes the metabolic imbalance, inefficient use of energy, and the high level of oxidative stress that damage morphological development and reproductive performance. The results suggest that energy distribution is shifted to maintenance and survival under stress, decreasing the energy in growth and reproduction. These effects are further increased with aging, which increases the overall physiological degradation. The paper establishes the value of nutritional balance in the maintenance of metabolic well-being and organismal fitness. It offers a comprehensive insight into the biological implications of consuming too much sugar by combining the perspectives of morphological, metabolic, and reproductive.

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